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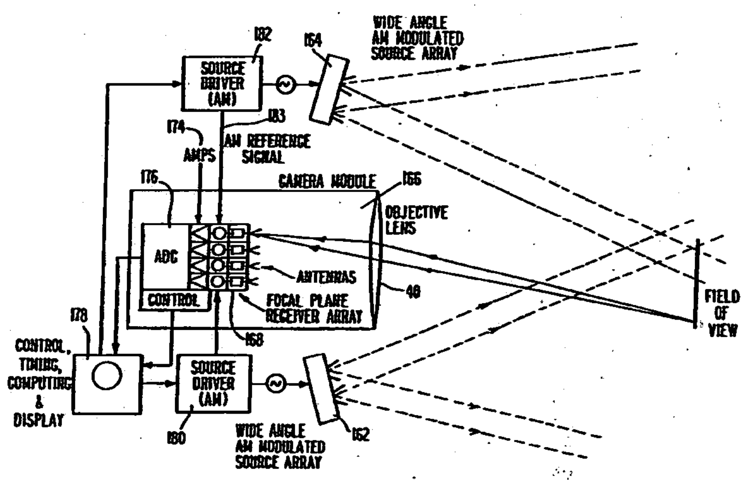

(57) Abstract

Millimeter-wave imaging elements and systems are disclosed. The system components may be used for navigation in fog or for other purposes, including a contraband detection system especially suited f r detecting concealed non-magnetic and non-metallic contraband such as ceramic or plastic weapons r illegal drugs. In this embodiment of the invention, plural sources (110) f quasi-coherent millimeter wave radiation are disposed so as to uniformly illuminate a field of view. The radiation emitted by the sources may be linearly polarized in a single plane such that the polarization of the radiation with respect to the plane in which linearly polarized radiation is preferentially received by the detectors can be controlled. For detection of dielectric objects, such as ceramic weapons or narcotics, these planes of polarization should be orthogonal to one another. The detector is a staring array (36) which does not require scanning to generate an image of the entire field of view.

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MILLIMETER - WAVE IMAGING SYSTEM, PARTICULARLY FOR CONTRABAND DETECTION

Field of the Invention

This invention relates to apparatus and methods for imaging objects using millimeter wave radiation. One particular system according to the invention detects weapons and contraband carried by persons, particularly weapons and contraband that cannot be readily detected using conventional electromagnetic inspection techniques. The system of the invention is sufficiently sensitive, accurate and rapid that it does not require lengthy inspection of persons passing into a secured area.

Background of the Invention

This invention relates broadly to the use of millimeter wave radiation, which pentrates material such as fog, smoke, clothing and organic matter which is opaque to visible light, to form images of objects. There are many applications of this invention. Referring first to the application of the invention to detection of contraband, it will be appreciated that present day personnel inspection systems designed to locate weapons which are employed at the portals of secured areas, e.g. courthouses, military installations and the like, normally rely upon electromagnetic detection of a mass of metallic material. Such systems

have been in use in airports for a number of years. However, the limitations of such systems are becoming increasingly significant. Electromagnetic systems are limited to the detection of magnetic items such as conventional handguns and therefore cannot detect the non-magnetic plastic and ceramic weapons now being manufactured and sold. Such electromagnetic systems also cannot form an image of the detected material; they merely respond to a mass of the metal passing the detector. Similarly, such systems are incapable of detecting other contraband, such as drugs or certain chemical explosives.

The prior art includes a number of proposed systems for detection of non-metallic weapons and other contraband. Many of these have relied upon the ability of millimeter waves (radiation of wavelength between one millimeter and one centimeter, that is, between 30-300 GHz frequency) to penetrate clothing without harm to the wearer. Millimeter waves are generally reflected from metallic objects and can be used to form an image of such objects. The attenuation and reflection characteristics of ceramic and plastic weapons, as well as contraband such as narcotics, are different with respect to millimeter-wave radiation from those of skin, so that it is possible, although it has not previously been practical, to form an image of objects of these materials carried by a person. These characteristics render millimeter waves suitable for detection of ceramic weapons or other contraband concealed beneath the clothing, for example, of an individual seeking to enter a secured area.

However, proposed prior art millimeter wave contraband detection techniques have not been implemented in practical systems. Prior art systems,

as exemplified in a number of documents discussed hereinafter, have in general involved a single millimeter wave detector, which is mechanically scanned over a field of view within which the individual is constrained to stand. The reflected signal can be processed and used to generate a television display. The systems of the prior art have at best required about 30 seconds to generate a suitable image. Clearly this is unsatisfactory for use in airports and other crowded areas where many individuals must be permitted to enter the secured area rapidly. Further, any image which requires a 30 second exposure is highly likely to suffer from blurring as the subject moves. Therefore, such systems have found little use.

Another defect of the systems proposed in the prior art involves the lack of contrast between non-metallic contraband articles and the skin of the subjects, particularly as compared to the high reflectivity of specular objects, e.g. belt buckles, eyeglasses, coins, watches and the like.

E. Reber, F. B. Foote, R. L. Schellenbaum, and R. G. Bradley, "Evaluation of Active and Passive Near Millimeter-Wave Radiometric Imaging Techniques for Detection of Concealed Objects", Sandia National Laboratories Report SAND 81-1051 (July 1981) discusses a far infrared (FIR) or near millimeter wave (NMMW) (300-3000 um, or 0.3-3mm) imaging system. A two-dimensional mechanical scanning system was used in conjunction with an NMMW radiometer to generate a video signal which drove a TV monitor. Active illumination was provided by a klystron. Incoherent illumination was also proposed, using a black-body radiating at 77K. A h terodyne detection approach was employed, using a

Schottky diode mixer and another klystron as a local oscillator source.

This reference discusses on page 15 that if a point source of illumination is used, large flat objects can fail to be detected if they reflect the illumination energy away from the detector, and states that a practical system will require a suitable illumination source. It is stated that ideally the entire hemisphere in front of the person being imaged would be illuminated. It was concluded that coherent illumination, as supplied by a klystron, was unsatisfactory. See page 19.

The time required for this system to form an image was approximately 2 minutes; this is obviously impractical for an airport personnel inspection system, for example. It was suggested that while this might readily be reduced to one minute, further improvements would require development of a detector array not then available. Image processing was also proposed.

R. L. Schellenbaum, "Far Infrared Contraband Detection System Development for Personnel Search Applications", Sandia Report SAND82-0161 (September 1982) follows the work discussed immediately above and investigated better illumination. A microwave Michelson interferometer was used as the experimental apparatus. A hybrid tee divided the radiation from a Gunn diode source between the field of view and a reference arm. The interrogation signal was mechanically scanned over the target. Hence, lengthy periods would again be required to generate an image. The target reflected the signal back to the detector via th hybrid tee. A variable short and attenuator in the reference arm controlled the phase and amplitude of

a reference signal received by the Schottky diode detector. This interferometric technique involved some unavoidable sensitivity to source-to-object distance, which was undesirable.

A number of alternative illumination schemes were also suggested. Among others, a large number of point sources was considered, but deemed impractical. Incoherent illumination provided by mercury lamps was considered inadequate. A system involving two collimated Gunn diode oscillators and two dispersing elements reflecting the energy onto an inner diffusing surface of a spherical chamber was suggested. This reference also discusses use of wire-grid polarizers to distinguish retroreflected target signal return (i.e. specular reflection from smooth metallic surfaces) from directly reflected body background (diffuse reflection from skin), concluding that the use of polarizers would not be fruitful.

Various documents suggest use of multiple element arrays for imaging millimeter wave radiation for astronomical imaging purposes, but contain no suggestion that such arrays might be useful for weapons or contraband detection. See Yngvesson, "Near-Millimeter Imaging with Integrated Planar Receptors; General Requirements and Constraints," in <u>Infrared and Millimeter Waves</u>, <u>10</u>, (Academic Press 1983). Fig. 8 of this document shows a Vivaldi receptor array. Further details of this detector system are shown in Yngvesson <u>et al</u>, "Millimeter Wave Imaging System with an Endfire Receptor Array", <u>10th Int'l Conf. on Infrared and Millimeter Waves</u> (1985). Diode detectors extending across pairs of antenna elements making up the detectors of the array are shown in Fig. 7. Similar disclosures are found in Johansson <u>et al</u>, "Millim ter Imaging System with an Endfir Rec ptor

Array", Proc. 15th Europ. Microwave Conf. (1985), in Korzeniowsky et al, "Imaging System at 94GHz using Tapered Slot Antenna Elements," Eighth IEEE Int'l Conf. on Infrared and Millimeter Waves (1983), and in Yngvesson, "Imaging Front-End Systems for Millimeter Waves and Submillimeter Waves," SPIE Conf. on Submillimeter Spectroscopy (1985). The method of injecting the local oscillator signal for heterodyning with the received signal shown in these references, involving injection of the signal into an aperture in a reflector in a Cassegrain-telescope optical system, is very awkward and cannot provide uniform illumination of all elements in the detector array. Such devices would not be well suited to contraband detection.

In Stephan et al, "A Quasi-Optical Polarization-Duplexed Balanced Mixer for Millimeter-Wave Applications," IEEE Trans. on Microwave Theory and Techniques, vol. MTT-31, No. 2 (1983) pp. 164-170, a mixer is described in which a local oscillator signal is quasi-optically injected from one side of a substrate and mixed in a balanced mixer with the received signal coupled from the other side. The RF signal and local oscillator (LO) signal can be of orthogonal polarizations. It is suggested that the LO signal could arrive from either side of the substrate, although no implementation of the "same-side" arrangement is provided. The suggestion is made that arrays of such devices could "open the way to phase-coherent imaging of millimeter-wave fields at a focal plane." See page 170. However, neither side of the substrate of this device in the embodiment disclosed would be available for other circuitry, as is highly desirable. There is no teaching in Stephan et al of a practical contraband detection device.

It is known that millimeter waves penetrate numerous adverse environments which are not transparent to optical or infrared rays. For example, millimeter waves penetrate fog, snow, blowing dust and sand, smoke, clouds of chemical gases, and other atmospheric constituents which absorb visible and infrared radiation, and therefore prevent image formation using systems operated at these wavelengths. For example, fog currently prevents landing of airplanes, simply because there is available no imaging technology enabling pilots to see the ground in fog. This is obviously highly inconvenient.

There are numerous other applications where it would be highly desirable to have a sensor not affected by these atmospheric constituents. For example, the rescue of an airman forced to eject from his aircraft over water, or of a capsized sailor, is very difficult in fog. Radio frequency beacons can be used to provide a rough position signal, but the wavelengths of such systems are so long that it is impossible to locate precisely an individual beacon with accuracy sufficient to rescue the individual. That is, a radio frequency beacon can be used to provide a "fix", but this is only sufficient to bring a rescue craft within visible range; hence such a system is only effective on clear days.

It is well known of course that microwaves penetrate fog, dust, smoke, etc. generally as do millimeter waves. However, the wavelengths employed by conventional microwave equipment are in general too long to provide accurate imaging using components of practical size. Similarly, microwave sources and detectors are physically so large that microwave

equipment is not suitable for numerous airborne and other applications where size and weight are critical.

Thus, while visible and infrared wavelengths are short enough to permit generation of an accurate image of a field of view, radiation in these bands is significantly attenuated by common atmospheric constituents, limiting the utility of such imaging systems. Lower frequency radiation such as radiofrequency energy and microwaves which are not attenuated by these constituents are of such long wavelengths as to be incapable of forming images, or require impractically large components, or both.

Millimeter waves (typically 1cm - 1mm wavelength, and 30-300 GHz frequency) are between the microwave and infrared radiation bands, and combine some of the advantages of each. Millimeter waves are attenuated by the common atmospheric constituents listed above, but only to a limited degree, such that image formation is possible under circumstances which prevent operation of visible-frequency or infrared systems. Millimeter waves are also of sufficiently short wavelengths that an accurate image of a field of view can be formed using components of sizes convenient to be carried by aircraft, spacecraft, satellites, and so on.

One reason why millimeter wave imaging systems have not heretofore been provided is because prior to the present invention (and those described in certain related applications by the same inventors) there has been provided no teaching of practical components for detecting millimeter wave energy emitted by or reflected from objects in a field of view which are suitable for forming an image.

Summary of the Invention

According to the present invention, a "staring" millimeter wave sensor comprising an array of detectors is provided. The staring sensor is directed at the field of view, so that each of the elements of the sensor provides a continuous signal responsive to radiation detected from a corresponding portion of the field of view. The output signals can be used to drive a video display unit or the like wherein each picture element (pixel) of the image corresponds directly to the corresponding portion of the field of view. In this way, scanning of the field of view by the sensor can be eliminated, permitting the image to be generated essentially in real time.

The present invention comprises a millimeter wave imaging sensor which in its simplest embodiment consists of a lens and an array of imaging elements. Each element of the array comprises an antenna, consisting of a balanced pair of conductive elements, and a non-linear circuit element such as a diode connected across the conductive elements. The antennas detect millimeter-wave energy reflected from or emitted by objects in the sensor's field of view, and the diodes rectify the detected energy, providing lower-frequency signals which can readily be combined to form an image. Each of the imaging elements of the sensor corresponds to a pixel of the ultimate image, such that a true focal plane array is thus provided.

In the simplest application of this sensor, each imaging element simply provides an output signal responsive to millimeter wave energy emitt d by objects in the corresponding portion of the field of view.

These signals can be employed to form a "radiometric" image of the scene. This could be used for example to generate a video image of the ground over which an aircraft is flying at any particular time. Alternatively, the output signal of each sensing element can be integrated over a period of time and used to form a "still" image, as in a time exposure made using a still camera.

If increased sensitivity is required, a local oscillator signal can be mixed with the incoming radiation in each of the antenna elements, thus substantially improving the signal-to-noise ratio of the detectors in a "superheterodyne" arrangement. The source of the local oscillator signal or a second source can also be employed to illuminate the field of view, for further sensitivity. The frequency of the illumination and local oscillator signals can also be varied with time, for object detection and ranging purposes. A corresponding image can be formed using conventional processing techniques.

In certain system applications, millimeter-wave sources in the field of view can also be employed, and their emitted signals may be modulation "encoded" for various purposes. For example, runway lights can be amplitude-modulated, e.g. by sine-waves, to enable a sensor carried by an aircraft to differentiate them from one another. An image corresponding to the pilot's "clear night" image of the airport can then be provided. Airmen and sailors may be provided with millimeter-wave emergency position-indicating beacons (EPIRBs) comprising millimeter-wave sources modulated according to a known pattern, to improve battery life and improve signal-to-noise ratio. Fixed objects (such as the tops of tall buildings, bridges, lighthouses and

the like) can be lighted with encoded millimeter wave sources as navigational aids. In general, wherever lighting is normally provided to enable nocturnal operations, a millimeter-wave source according to the invention may profitably be added. In each case, use of millimeter-wave sources and detectors according to the invention eliminates interference with normal operations due to fog, snow, rain, blowing sand, etc.

In the contraband detection system of the invention, arrays of sources of linearly polarized millimeter wave radiation are disposed to illuminate the field of view uniformly, for example on either side of the sensor array. The arrays consist of a number of oscillators which are <u>not</u> all constrained to operate at the same frequency, although they are aligned such that all the radiation exhibits polarization in a single plane. Normal variations in the manufacture of the oscillators provide enough variation in their physical characteristics that they do not resonate at the same frequency, thus providing substantially incoherent illumination from a number of sources, each of which itself emits coherent radiation. It has been discovered that such "quasi-coherent" radiation, provided from spatially diverse sources which distribute the illumination over the field of view, mitigates both "glint" and "speckle" effects in the image. "Glint" results from specular reflection of coherent or incoherent point-source radiation, e.g. the sun shining on an automobile windshield, while "speckle" is an interference effect occurring upon reflection of coherent radiation, e.g. visible laser light reflecting from a wall. According to this aspect of the invention these two common problems are circumvented.

In accordance with anoth r asp ct of the invention, the radiation emitted by the oscillators is preferably polarized. In most cases, linearly polarized illumination radiation is preferred, and a detector is used which is preferentially sensitive to radiation linearly polarized in a particular plane. The polarization of the radiation and the sensitivity of the detector are then controlled in accordance with the particular contraband to be detected in order to minimize noise in the reflected signal by reducing signal return from metallic items, skin, clothing or other superfluous objects, referred to herein as "clutter". Elliptically or circularly polarized radiation can also be employed and the detection apparatus adjusted to yield the best image of the particular contraband to be detected.

Where the contraband is non-metallic, e.g., ceramic weapons, narcotics, plastic explosives or the like, it is found in accordance with the invention that the best image can generally be obtained by making the detector array preferentially selective to radiation polarized orthogonal to the polarization of the illumination radiation. This is referred to herein as the "orthogonal" arrangement. When the incident and preferentially detected radiation are thus orthogonal to one another, detection of retroreflected radiation from metallic objects in the field of view is greatly reduced, as is radiation directly reflected from clutter. However, ceramic and plastic objects, particularly of complex shapes, and granular materials such as quantities of narcotics, reflect incident polarized radiation in this spectral region in essentially random fashion, such that some radiation becomes polarized in the plane f the detector sensitivity.

As the reflection from clutter is attenuated due to the orthogonal arrangement of the sources and detector, the signal-to-noise ratio of the system with respect to amorphous plastic and ceramic objects and granular materials such as narcotics is much improved. The millimeter wave radiation apparently undergoes multiple internal reflections in plastic or ceramic objects such as weapons, so that the polarization of the radiation is varied somewhat, whereby it can be detected by the detector array.

Metallic objects are still detectable by an observer with the system in this orthogonal arrangement; only specular metallic surfaces do not appear in the image generated by the detector array. For example, the cross-hatched grips conventionally used on pistols, the lines at which the planes of their surfaces meet, curved surfaces, and the like are imaged relatively well. It is also possible to vary the relative polarization of the radiation and the detector sensitivity to generate images of both metallic and non-metallic objects.

The ability of the staring sensor of the invention to provide individual output signals corresponding to each element of the array allows very simple processing of these signals to form a video signal, and also renders them readily amenable to digital signal processing techniques used to improve the contrast of the signal reflected from the contraband relative to the skin of an individual, to reduce graininess in the images, or to provide other practical image enhancements. These techniques are currently within the skill of the art.

The preferred oscillat rs comprise Gunn diodes or other solid-state oscillators. However, klystrons and other sources of millimeter-wave radiation at a single frequency (as opposed to black-body radiators emitting energy over a wide spectrum) are also suitable, if somewhat less practical.

Where linearly polarized radiation is used, the Gunn diode oscillators which are preferably employed are formed on substrates which define the plane of polarization of linearly polarized radiation emitted by the sources. The sources are aligned so that all emit radiation polarized in the same plane. The detecting array typically comprises an array of detectors, each comprising a pair of planar antenna elements formed directly on the supporting substrate. These elements are preferentially sensitive to linearly polarized radiation polarized parallel to the plane of the substrate.

Brief Description of the Drawings

The invention will be better understood with reference to the accompanying drawings, in which:

Fig. 1 shows a schematic view of prior art systems which unsuccessfully attempted to detect non-metallic contraband on the persons of individuals;

Fig. 2 shows a schematic plan view of the system according to the present invention for detecting contraband;

Fig. 3 shows an elevation view of the source and detector elements of a system for detecting contraband according to the invention;

Figure 4 shows a perspective view of a portion of the detector array of the invention;

Figure 5 shows a plan view of a portion of the detector array of the invention;

Figure 6 shows schematically the signal path provided by a single element of the detector array in a first embodiment of the invention;

Figure 7 shows schematically the signal path in a single element of the detector array in a superheterodyne embodiment of the invention;

Figure 8 shows schematically the signal path in a single element of the detector array in an illuminating superheterodyne embodiment of the invention;

Figure 9 shows the optical arrangement of an embodiment of the invention corresponding to Figure 6;

Figure 10 shows the optical arrangement of the invention in an embodiment corresponding to Figure 7;

Figure 11 shows an optical arrangement of the invention in an embodiment corresponding to Figure 8;

Figure 12 shows an alternative embodiment of the optical arrangement of the system of the invention corresponding to Figure 8;

Figure 13 shows a plan view of an array of a first embodiment of millimeter wave oscillators which can be used as a source of millimet r wave energy;

Figure 14 shows a cross sectional view taken along the line 14-14 of Figure 13;

Figure 15 shows a cross sectional view through a Schottky barrier diode which can be employed in each element of the imaging array of the invention;

Figure 16 shows a cross sectional view of a twist reflector which can be used in the embodiment of the invention described in connection with Figures 8 and 11;

Figure 17, comprising Figures 17(a)-(e), shows integrated circuit embodiments of millimeter wave sources which can be employed in connection with the invention; and

Figure 18 shows a cross-sectional view along the line 18-18 of Figure 17.

Description of the Preferred Embodiments

As indicated above, this application relates to a millimeter wave imaging sensor, comprising an array of detectors disposed in the focal plane of an optical system for receiving millimeter wave energy from the field of view and for providing output signals which can be used to form an image corresponding to the millimeter wave energy received from the field of view. An embodiment of the invention in which it is employed for contraband detection is described first. Subsequently a basic "building block" sensor array according to the invention is described. Several different embodiments of the sensor in combination with

other devices ar then d scribed. Various systems employing the sensors of the invention are finally described briefly.

Figure 1 shows a prior art contraband detection device as proposed but not successfully implemented. Millimeter-wave radiation from a field of view is effectively scanned by rotation of first mirror 150 about a vertical axis indicated generally at 152, and by scanning of a second mirror 154 about a horizontal axis. Other mechanical scanning techniques are known. Radiation from the field of view is reflected from a primary mirror 153 and detected by a radiometer 156. Processing electronics 158 receive synchronization signals from the vertical and horizontal mirrors and use these to convert the raster-scanned signal from the field of view into a video signal used to drive a display. The art suggests as indicated above that noncoherent sources of illumination, e.g. mercury lamps, could be used to provide illumination, as indicated at 155. As discussed above, a principal defect in this system among others is that typical scanning times amount to thirty seconds or more. This is unacceptable for screening passengers at airports, for example.

Figure 2 shows in plan view a contraband detection system in accordance with the invention. Figure 3 shows a front elevation of the sources and detector arrays used. In Figure 2, two source arrays, 162 and 164, are shown disposed to illuminate the field of view evenly; for example, the panels could be disposed on either side of the detector array, depicted as a camera module 166. The arrays consist of at least two point sources of millimeter-wave radiation; larger numbers of sources will provide more even illumination

and are preferred. In an airport portal inspection system, arrays 162, 164 might be configured as roughly 3 x 6 foot panels made up of Gunn diode oscillator assemblies each 9 inches square, which might each include nine oscillators. The panels might also be disposed on opposite sides of a passageway, with the camera module 166 being aligned along the passageway.

According to one aspect of the invention, each of the source arrays of the contraband detection system emits "quasi-coherent" radiation, meaning that radiation is emitted by a number of oscillators which are not constrained to operate at the same frequency, but among which the resonant frequency distribution need be no greater than inherent in normal manufacturing variation to achieve the desired results. The term "quasi-coherent" as used herein further indicates that the radiation from all sources is of the same polarization. Typically, in the system arrangement shown in Figure 2, the radiation emitted by the two sources 162, 164 would be linearly polarized in the horizontal plane.

It will be appreciated that linear polarization is but one special case of polarized electromagnetic radiation, which is generically termed elliptically polarized. Circularly polarized radiation is another such special case. For reasons which will appear hereinafter, linearly polarized radiation is emitted by the sources 162 and 164 in the preferred embodiment of the system of the invention. However, it must be understood that many of the advantages provided by the invention would also be realized if circularly or elliptically polarized radiation were employed.

Th detect r array, shown schematically at 168 and in more detail in connection with Figures 4-11, is preferentially sensitive to radiation polarized in a particular manner, which according to an important aspect of the invention is controlled with respect to the polarization of the radiation emitted by the sources. Where a system employing linearly-polarized radiation is to be employed to detect dielectric contraband such as ceramic weapons, narcotics, or certain non-metallic explosives, detectors preferentially selective to radiation linearly polarized in a particular plane are used. More specifically, applicants find that the plane of the polarization of the radiation to which the detectors are preferentially sensitive should be orthogonal to the plane of polarization of the illuminating radiation.

In order to detect contraband such as conventional metallic weapons, nuclear materials or certain metal-encased explosive materials, better imaging may be achieved by aligning the plane of polarization of the emitted radiation parallel to (rather than orthogonal to) the plane of preferential sensitivity of the detector array. Accordingly, the plane of polarization of the radiation emitted by the sources may be switched relatively rapidly over time to change the sensitivity of the system. This can be accomplished simply by rotating the source array through 90°, by rotating polarizing grids in front of the camera 166 and/or the sources in certain embodiments thereof, or by electronically varying the plane of polarization of the radiation emitted by stationary sources.

The camera 166 includes an obj ctive lens 40 which focuses radiation from the field of view onto a focal plane in which lie the individual elements of the detector array. Each provides an output signal the amplitude of which corresponds to the intensity of the radiation from the corresponding portion of the field of view. Source drivers 180, 182 drive the source arrays. The sources are amplitude modulated by the source drivers, e.g. at 1-10kHz, so that the signal detected by the elements of the receiver array is an ac signal. Otherwise, a dc signal would be detected, which would be more difficult to process.

Preferably, the illuminating radiation is amplitude modulated using a square wave, i.e., an on-off signal. The signal detected by the detectors with the illumination sources off is background, noise, etc., which is consistently detected. Therefore this can be subtracted from the signal detected while the illumination sources are on (i.e., the reflected illumination signal plus the background) to yield the reflected illumination signal only. Such synchronous detection schemes are commonly employed in electronic systems generally to increase the system signal-to-noise ratio.

The detected signals are amplified in amplifiers 174. The amplified signals are provided to analog-to-digital converters which in turn are connected to a control, timing, computing and display unit 178. This unit converts the individual digital signals output by the analog-to-digital unit 176 into a video signal for display. Alternately, the signal provided by the analog-to-digital converter 176 can first be signal processed using any of a wide variety of digital signal

processing techniques, for example to increase the contrast within the signal.

Fig. 3 shows as mentioned a front elevation of the source arrays 162, 164 and of the camera 166 of the system shown in Fig. 2. This embodiment of the system of the invention is envisioned for use in airport monitoring, e.g., to control secured areas. In this embodiment of the system it might also be desired to feed a local oscillator signal into each of the elements of the detector array for mixing with the received signal. The local oscillator signal provides a superheterodyne effect; as is well known to those of skill in the art, this substantially increases the signal-to-noise ratio of the system. According to the present invention, the local oscillator signal if used may be combined with the received signal separately in each of the elements of the array using a quasi-optical technique discussed in detail below.

In additional embodiments of the invention it may also be desired to use the same oscillator to provide some or all of the illumination of the field of view as well as the local oscillator signal for demodulation of the received signal. This is useful in forming a small, compact, possibly even hand-held unit for scanning contraband conveniently, in circumstances where setting up a permanent portal detection system would be inappropriate.

As mentioned, one way to provide time variation of the polarization of the illumination radiation with respect to the preferentially detected plane is to alternately transmit the radiation from emitting antennas orient d along orthogonal axes. Duplicate sets of oscillators and orthogonal associated

transmitting antennas may b provided on the source panels described above; the modulating signal can then be alternately applied to the oscillators of the orthogonally aligned groups of emitters. The same oscillators may, as an alternative, be alternately connected to orthogonal transmitting antennas. Improvements in PIN diode technology over that available as of the filing of this application are anticipated which would make this embodiment practical.

Figure 4 shows a perspective view of a portion of the antenna/detector array 36 used in all embodiments of the camera 166 of the invention, while Figure 5 shows schematically a plan view of a portion of a substrate 70 on which conductors 68 making up the individual elements 66 of the array 36 of antenna/detector elements are formed, and a portion of the associated circuitry. Array 36 comprises a plurality of substantially identical imaging antenna/detector elements 66. Each imaging element 66 comprises a balanced pair antenna which may be formed directly on a dielectric substrate 70 such as Kapton (TM) in turn supported on an alumina panel. These assemblies are spaced from one another by a precision spacer member 72. The outline of the antenna elements 68 in a preferred embodiment is shown in Figure 5. As indicated, the array elements 66 each comprise two spaced conductors 68 each comprising parallel portions 73 which extend a distance into the array 36 (the incident radiation being received endwise in the view shown in Fig. 4), curved portions 74 which approach one another along curved outline, and further portions which are separated by a slot 76 and extend for another distance.

Such antenna elements 66 are referred to in the art as "endfire traveling wave slot antennas", as originally described by P.J. Gibson, "The Vivaldi Aerial", Proc. of the European Mic. Conf., Brighton, UK (1979), pp. 101-105. A nonlinear circuit element 80, such as a diode or other square-law detector, is connected across the pair of conductive elements 68 of each antenna 66. In a preferred embodiment of the invention, the imaging array 36 may comprise an array 100 x 100 of antenna/detector elements 66, resulting in 10,000 identical antenna/detector elements 66 in the overall array 36. This is adequate to provide quite reasonable resolution, for example, to produce a visible image of the field of view.

The function of the non-linear circuit elements 80 varies somewhat depending on the embodiment of the invention. In the simplest embodiment of the invention (discussed further in connection with Figures 6 and 9), the antenna elements 68 simply detect millimeter wave radiation received from the field of view. The diodes 80 connected across the paired antenna elements rectify the input energy, and provide an output signal which follows the envelope of the input millimeter wave energy. For example, suppose that the field of view includes a person carrying a concealed weapon. An image can readily be formed which will clearly locate the relative position of objects in the field of view which reflect or partially attenuate millimeter wave radiation more or less than other portions of the field of view. The weapon will show up as a dark or light area, depending on its relative reflectivity. The bandwidth of the energy detected is simply a function of the design of the imaging elements 66.

In a further embodiment of the invention, discussed in connection with Figures 7, 8, and 10-13, the diodes also mix a local oscillator signal with the millimeter wave energy received from the field of view. As is well understood, the mixing process results in sum and difference components. The sum component is typically discarded, and the difference component signal is processed to yield the intensity of the corresponding pixel of the image. Mixing the local oscillator signal with the received energy in each element of the array greatly increases the signal-to-noise ratio of the system. If each imaging element of the sensor array of the invention in its simplest embodiment is analogized to a simple crystal detector radio set, then each imaging element of the sensor array in its embodiment in which a local oscillator signal is mixed with the received signal is comparable to a superheterodyne receiver.

It will be appreciated therefore that the diodes perform the rectifying or envelope detection function where no local oscillator signal is provided or perform the mixing function if the local oscillator signal is provided. Reference in the following to "mixer" diodes should be understood to include diodes solely performing the rectifying or envelope detection function unless the context indicates the contrary.

As indicated, each antenna/detector element 66 comprises a pair of conductors 68, each of which has a relatively thin forward section 73 extending toward the field of view, an exponential middle section 74, and a terminal slot 76 separating the two elements 68. Diodes 80 are connected across the conductors 68, as indicated by Fig. 5. In a preferred embodiment, slot 76 has two additional slots 78 extending from either

side thereof and orthogonal thereto. These sl ts 78 comprise a radio frequency choke which reflects any unrectified millimeter-wave energy as well as the sum of the local oscillator and detected signals formed upon their mixing, while passing the difference signal.

As noted, the actual envelope detection and mixing functions are performed by a nonlinear circuit element, e.g., a diode 80, which is preferably physically disposed between the two conductive elements 68 of each element, that is, directly across the slot 76. In a preferred embodiment discussed in detail below, the diode 80 is formed directly on the substrate 70 without separate connecting leads.

After envelope detection or mixing of the local oscillator signal and the signal from the field of view by diodes 80, and filtering by the RF chokes formed by the slots 78, the signal which remains is a relatively "clean" intermediate frequency signal which can be amplified by conventional operational amplifiers 82 associated with each element 66 of the array 36. The output signals from amplifiers 82 can be supplied directly to the image formation or other radar signal processing circuitry 22 as indicated above.

Figure 6 shows schematically the arrangement of each of the elements 8 of the array 36 in a first "radiometric" embodiment of the invention, wherein the array simply detects millimeter-wave energy reflected from objects in the field of view (FOV). The signal 12 is detected by an antenna element 10 and rectified by a diode 4. The signal resulting is amplified by an amplifier 18 and is supplied together with a large number of like signals 20 to generally conv ntional

image generati n and signal processing circuitry 22. The signal-to-noise ratio of the signal from elements 8 as shown in Figure 6 may also be increased by connecting a storage element, indicated schematically as a capacitor 19, for storing the energy rectified by the diode 4.

Generally, all objects emit millimeter wave radiation, at frequencies and amplitudes which are functions of the temperature of the objects and their emissivities. The "radiometric" sensor array described above is receptive to such millimeter wave radiation emitted by or reflected from objects in the field of view. Such an array of sensors could be used to provide a continuous image of a region over which an aircraft were flying. The image could be provided on a "head-up" display for the pilot's convenience. The scene could additionally be illuminated by millimeter-wave "landing lights" carried by the aircraft, and might also include millimeter wave beacons 1 at spaced locations on an airfield, for example, corresponding to the common locations of runway and taxiway lights. These beacons 1 could also be sinusoidally or otherwise modulated in a manner readily detectable by the signal processing circuitry 22. Such a system would also be suitable for detection of millimeter wave energy received from a beacon carried by a downed airman, a capsized sailor, or the like. In many such applications, it is anticipated that the sensitivity of the imaging array of the invention will be usefully increased by heterodyning the received energy with a local oscillator signal as discussed below.

Figure 7 is a block diagram showing the individual signal processing components employed in each of a large number of mixer/detector elements 8 in

a superheterodyne embodiment of the imaging device of the invention. A millimeter-wave oscillator 26 provides a local oscillator signal which is mixed with the reflected radiation 12 to provide a lower frequency signal for convenience in signal processing, and to increase the signal-to-noise ratio with respect to the embodiment of Fig. 6. Figure 8 is a block diagram of a similar system in which the energy 34 provided by the millimeter wave oscillator, used to provide the local oscillator signal, is also used to illuminate the field of view with millimeter-wave radiation. In both cases an antenna 10 detects radiation reflected from or emitted by objects in the field of view. Energy 12 detected from the field of view at frequency f_{sig} and the local oscillator signal 14 at frequency f_{LO} are combined in a mixer 16. The difference signal, at frequency $|f_{sig}-f_{LO}|$, is supplied to a video or radio frequency amplifier 18. The amplified signal, together with a number of similar signals 20 from other identical elements 8 of the array, is supplied to signal processing circuitry 22 for generation of an image, or other purposes.

Where the field of view is illuminated, the overall system termed is "active"; otherwise, it is "passive". The detector embodiments of Figs. 6 and 7 can be employed in either active or passive systems. The Fig. 8 embodiment, since the local oscillator then also illuminates the field of view, is always active.In each embodiment of the detector, a large number, e.g., 10^4, of the mixer/detector elements 8 shown schematically in Figures 6, 7 and 8 are arranged in a detector array, as generally shown in Figs. 4 and 5. The signal output by each element 8 corresponds to a portion of the field of view; if an image is to be formed, each element 8 may be taken to correspond to

one or several particular picture elements ("pixels") of the image. In the case of the Fig. 6 embodiment, the signal is simply the "envelope" of the energy emitted by or reflected from objects in the field of view. In the Figs. 7 and 8 embodiments, the signal output by each element 8 is a signal the frequency of which is responsive to the absolute value of the difference between the frequency of the received signal 12 and the frequency of the local oscillator signal 14. The amplitude of the image signals is approximately proportional to the amplitude of signal 12.

Accordingly, since a multiple element focal-plane array is used, in which each element of the detector array is mapped to a portion of the field of view, a single image-forming element need <u>not</u> be scanned either mechanically or electronically over the field of view, as shown in the proposed contraband detection systems discussed in the literature mentioned above. For example, an ordinary analog video signal can be generated simply by successively interrogating each of the imaging elements 8 along successive rows of the array of elements, as is done in cameras using a CCD imaging device.

It will be appreciated as well that the rectification or envelope detection and mixing functions (where mixing is performed) are provided by nonlinear elements which are integrally combined with each of the antenna elements 10 by which the energy is coupled into each of the nonlinear elements. Accordingly, no waveguide structure or like complication is required to combine the local oscillator signal 14 with the signal 12 received from the field of view. This greatly simplifies construction of the sensor according to the invention.

It is anticipated that contraband detection systems according to the invention which are intended for control of secured areas, e.g. airport departure areas, will employ the Fig. 6 system; in this application, the local oscillator is not anticipated to be required, as the illumination can be made quite powerful simply by multiplying the number of oscillators in the sources, 162, 164. If this is inconvenient, a local oscillator can be used to increase the signal-to-noise ratio, thus employing the Fig. 7 detector. Further, if it is desired to combine the radiation source and detector into a single device, e.g., as a handheld contraband detector for examining baggage or the like, the Fig. 8 detector might be chosen. In this case, however, the reduction of glint and speckle which are obtained by use of spatially distributed sources of quasi-coherent illumination in other embodiments of the invention will not be realized.

Fig. 8 shows an embodiment of the imaging array of the invention in which the energy output by a millimeter wave oscillator 26 is split into unequal parts. The minor portion 30 is used as a local oscillator signal, while the major portion 24 is transmitted as an illumination beam 24 onto the field of view. More particularly, the millimeter-wave energy signal 34 generated by the source 26 is linearly-polarized, such that it can be split into major and minor components 24 and 30 respectively by a polarizing grid 28. The major component 24 is employed as an illumination beam after reflection from the polarizing grid 28. The minor portion 30, which may include approximately 10% of the total signal energy output by the source 26, passes through the polarizing grid 28.

It is then reflected from a twist reflector 32, which rotates its polarization through 90°, and back onto the grid 28, which reflects it toward the array of mixer/detector elements 8. The minor portion 30 thus becomes the local oscillator signal 14, which is then combined with the reflected signal 12 from the field of view.

Accordingly, it can be seen that in the Fig. 8 embodiment the energy 34 from oscillator 26 is used both as an illumination beam 24 to illuminate the object and as the local oscillator signal 14 which is mixed with the signal 12 reflected from the field of view 12.

Figure 9 shows a possible optical arrangement of the millimeter wave detection device corresponding to Figure 6. A lens 40 (which could be replaced by a focusing mirror) collects millimeter-wave radiation from the field of view. A high pass filter 42 will typically be provided. The detector array 36 described in connection with Figures 4 and 5 is in the focal plane of lens 40; as indicated above, each element of array 36 outputs a signal corresponding to millimeter wave energy received from a corresponding portion of the field of view. A true focal plane array imaging system for millimeter wave radiation is thus described. This embodiment of the detector array of the invention is envisioned for use in conjunction with arrays of sources of radiation which in total is quasi-coherent, as described above for contraband detection systems for protecting secured areas, e.g. airport departure areas. An optional polarizing grid 43 may also be provided to further control the polarization of the detected radiation.

Figure 10 shows the c rresponding view of the system of Figure 7. In this case a source array 26 emits polarized millimeter wave energy which is incident on a polarizing grid 28 to be described below. This local oscillator signal is combined in array 36 with energy received from the field of view, generally as described above. Figure 10 thus shows the optical arrangement of the superheterodyne detection system of the invention. Again a high pass filter 42 and a polarizing grid 43 may be used to further reduce noise in the detected signal.

Figure 11 shows a possible optical arrangement of the millimeter wave signal detecting system discussed above in connection with Figure 8. In this embodiment, the local oscillator is also a source of illuminating radiation. This device may thus be employed as a self-contained portable contraband detection device. Of course it may also be used together with supplemental illumination sources 162, 164, or beacon 1. Incident radiation 12 from the field of view passes through lens 40, optional high-pass filter 42, an optional quarter-wave plate 46 (to be described) and polarizing grid 28, after which it is combined with a local oscillator signal emitted by a source 26 of millimeter wave energy. As discussed above, the linearly polarized radiation 34 emitted by the source 26 is divided by the polarizing grid 28 into major and minor portions 24 and 30 respectively. The major portion 24, desirably including about 90 percent of the millimeter wave energy, passes outwardly as indicated at 48 to illuminate the field of view with millimeter wave radiation. The remaining minor portion 30 of the radiation 34 emitted by the source 26 is incident on a twist r flector 50. This device, which is describ d in connection with Figure 16, has the property of rotating

the polarization of the linearly polarized incident energy by 90°. Accordingly, when the twist reflector 50 reflects the minor component 30 of the radiation back onto the polarizing grid 28, it is then reflected towards the mixer/detector array 36, and becomes a local oscillator signal 14 for combination with the portion of the illumination beam 24 having been reflected from the field of view. An alternative arrangement is shown in Fig. 12.

The system elements shown in Figures 9, 10, and 11 are generally referred to as quasioptical or as employing Gaussian optics. These terms refer to the fact that the wavelength of the radiation is comparable to the aperture of the array elements, such that diffraction effects are highly significant, and conventional straight-line ray tracing analytical techniques cannot be used. For example, lens 40 is generally as described in Goldsmith et al., "Gaussian Optics Lens Antennas", Microwave Journal, July 1984.

The polarizing grid 28 (and grid 43, if used) may comprise a series of parallel conductors spaced from one another by a dielectric medium. Such components are commercially available from the assignee of this application. In a particularly preferred embodiment, the conducting members may be spaced parallel wires, e.g., of tungsten coated with gold, spaced in air. A less expensive alternative is to photolithographically deposit flat conductive strips onto a dielectric substrate, e.g., Mylar (TM). In either case, the orientation of the conductors (which are indicated generally at 44 in Figures 10 and 11), with respect to the direction of polarization of the electric field of the millimeter wave energy 34 emitted by the source 26, determines the fraction of the incident millimeter wave

energy which is reflected from the grid 28; the remainder 30 passes through the grid 28.

More particularly, in a preferred embodiment, the spacing of the conductors 44 is approximately equal to or less than the wavelength of the millimeter wave radiation emitted by the source 26 divided by five. This grid 28 transmits the component of the linearly polarized electric field which is perpendicular to the direction of the conductors and reflects the portion which is parallel to their direction. If the conductors 44 are angled with respect to the direction of polarization of the radiation, a corresponding fraction passes through, and the remainder is reflected.

The filter 42 is generally as described in Goldsmith, "Designing Quasioptical Systems", in <u>The Microwave System Designers Handbook</u>, Fifth Edition (1987), and may comprise a metal plate having an array of holes drilled therein to provide a high pass filter for the millimeter wave radiation of interest.

As indicated, a quarter-wave plate 46 may be interposed between the polarizing grid 28 and the lens 40, in the Fig. 11 embodiment of the detector. The quarter-wave plate 46 is a known component which converts a linearly polarized incident wave, such as that emitted by the source 26, into a circularly polarized wave. Such a circularly polarized wave may have more desirable reflection characteristics from an object to be imaged than the linearly polarized wave; for example, a linearly polarized wave can be reflected asymmetrically depending on the particular orientation of the object, whereas a circularly polarized wav has more uniform reflection characteristics. Upon

reflection of the circularly-polarized wave from the object, the quarter-wave plate 46 will reconvert it to a linearly polarized wave, such that it will pass through the polarizing grid 28 without substantial attenuation. The quarter-wave plate may be manufactured from crystalline sapphire or by machining appropriate grooves into a dielectric material such as Rexolite (TM).

In the Figs. 9 and 10 embodiment of the detector, a similar quarter-wave plate may be placed behind the lens 40 and comparable devices placed between the source arrays and the field of view. The latter would convert the linearly polarized emitted radiation to circularly polarized radiation.

The twist reflector 50, which is used only in the Figs. 8 and 11 embodiment, is shown schematically in Figure 11 and in more detail in Figure 16. The twist reflector 50 comprises a number of generally concave or dish-shaped elements arranged in an array. Preferably, the number of elements in this array is equal to the number of elements in the array of millimeter wave emitters making up source 26. The shape of the concave elements of the array 50 is such as to focus the divergent beams emitted by the elements of the source 26 onto a corresponding area on the surface of the array 36 of mixer/detector elements after reflection from the polarizing grid 28.

As indicated in Figure 16, the twist reflector 50 comprises a dielectric substrate 56 coated on its rear side with a conductive layer 58, and on its front surface with a series of strips 60 of conductive material oriented at 45° to the direction of polarization of the incident wave. The thickness of

the dielectric 56 is one-quarter wavelength, such that the effective travel distance of the wave through the dielectric is one-half wavelength. Accordingly, when a component 57 of the incident wave 30 which is reflected from the rear conductive layer 58 is combined with a component 59 directly reflected from the strips 60, they will be 180° out of phase. This is equivalent to rotating the direction of polarization of the incident beam by 90°. Accordingly, the beam 30 incident on the twist reflector 50 (which, it will be recalled, had passed through grid 28) is effectively rotated by 90° with respect to the polarizing grid 28. When the rotated beam is again incident on grid 28, it is, therefore, reflected onto the array 36. Preferably, the concave elements of the twist reflector 50 are square and are fitted into a mosaic, in which as mentioned each element corresponds to one of the emitters of the source 26.

Figure 12 shows an alternative optical arrangement of the detector of the system of the invention in the Fig. 8 and 11 embodiment in which the twist reflector 50 is eliminated. Again a transmitting array 26 located in the focal plane of the lens transmits linearly-polarized millimeter-wave energy onto a polarizing grid 28 which directs it towards a field of view (FOV). The transmitted energy travels through a quarter wave plate 46 which transforms it from a linearly polarized beam to a circularly polarized beam. The circularly polarized beam is then incident on lens 40′ which in this case is a meniscus lens, that is, a concave-convex lens. The meniscus lens may be formed of materials such as Rexolite (TM) or Teflon (TM). See the Goldsmith and Goldsmith et al articles discussed above. A portion of the incident radiation is reflected from the lens 40′ and becomes

the local oscillator signal. As is well known to those of skill in the art, the precise amount of the radiation reflected can be controlled as needed by the employment of known anti-reflective coatings on the surface of lens 40'. The remainder of the energy incident on lens 40' is transmitted therethrough to become the illumination beam. The quarter-wave plate 46 transforms the circularly-polarized reflected local oscillator portion of the beam back into a linearly-polarized beam, but at a polarization of 90° to the original energy, so that it passes through the polarizing grid 28 and is incident on the mixer/detector array 36. A high pass filter may be employed as indicated at 42.

Accordingly, in this embodiment of the invention, the twist reflector 50 of Figures 2 is replaced by the meniscus lens 40', which has the property of passing a major portion of the energy to become the beam which illuminates the field of view while reflecting a minor portion of the energy to become the local oscillator signal which is then incident on array 36.

In this embodiment of the invention, the polarizing grid 28 need not be aligned with respect to the polarization of the energy from the source array 26 in order to divide the energy into local oscillator and illumination portions; this function is provided by the intrinsic characteristics of the meniscus lens 40', optionally in conjunction with an anti-reflective coating as discussed above. Both the local oscillator portion of the energy from the source and the energy reflected from objects in the field of view pass twice through the quarter-wave plate 46. This provides a 90° change in polarization dir ction, so that the energy passes through the polarizing grid 28 and is incident

on the mixer/detector array 36. One advantage of this design is that depending on various parameters it may be somewhat simpler to fabricate the meniscus lens than the twist reflector.

Other optical arrangements are possible. For example, a Faraday rotator can be substituted for the quarter wave plate in the embodiment of Figure 12. The Faraday rotator is described in the Goldsmith article, "Designing Quasioptical Systems", referred to above. The Faraday rotator provides 45° rotation of the polarization beam such that both the minor local oscillator portion of the emitted energy and the energy reflected from objects in the field of view are rotated through 90°. In this case, the illumination beam would be linearly polarized (rather than circularly polarized, as when the quarter-wave plate is used). This may be desirable, depending on the reflection characteristics of the objects to be imaged.

A further possibility would be to provide a Faraday rotator and mirror combination in place of the twist reflector described in connection with Figure 11. Again this combination could reflect the local oscillator portion of the beam and rotating its polarization through 90°, such that on its second incidence on the polarizing grid 28, it would be reflected therefrom to become a local oscillator signal for mixing with the received signal from the field of view in the array of mixer/detector elements 36.

As previously described, detection of the orthogonal polarization reflected signal is advantageous for imaging certain types of contraband. In order to effect this in conjunction with the systems shown in Figs. 11 and 12, other polarization elements

can be employed. The quarter-wave plate 46 described in connection with Fig. 11 can be replaced by a half-wave plate, oriented such that it rotates the polarization of the illumination and reflected beams each by 90°. See the Goldsmith and Goldsmith et al articles described previously. An additional Faraday rotator effecting a 45° rotation can be disposed between the meniscus lens 40′ and the (optional) high pass filter 42 in Fig. 12 to accomplish the same result.

As indicated above, according to an important aspect of the invention, quasi-coherent radiation (radiation which is linearly polarized in a single plane, but which is not frequency or phase coherent) from multiple element sources 162, 164 is transmitted into the field of view.

Figure 13 is an end-on view of one embodiment of typical source oscillator arrays 26 which can be employed both as local oscillator sources (Figs. 7, 8, 10 and 11) and as illumination sources 162, 164 (Figs. 2 and 3). In this embodiment of the oscillator sources, waveguide oscillators are used. A second embodiment of the source array, in which millimeter-wave integrated circuits are employed, is discussed below in connection with Figure 17. Either type of source oscillator could also be employed in beacons 1 (Figures 6,7 and 8).

In both cases, Gunn diode oscillators are shown; other solid state oscillators (e.g, IMPATTs) are of course also usable, as are klystrons, although the latter are currently less practical. The functional requirement is for a source of single frequency energy of appropriate frequ ncy with linear polarization.

The array of Figure 13 comprises a number of identical elements 112. Figure 14 is a cross section taken along line 14-14 of Figure 13, and shows a detail of one of the elements 112 in the source array 26. Each element 112 comprises a linear oscillator cavity 114 including an integral radiator horn output section. The active element is a Gunn diode element 116, the construction of which is generally conventional. The cavity comprises a radial disc resonator 118 located along a coaxial RF choke structure 119 which supplies DC bias to the Gunn diode element 116. A fixed backshort 117 is used to optimize the performance of the basic oscillator. This type of element is referred to in the art as a "waveguide cavity resonator" which is driven by the Gunn diode.

As can be observed from Figure 14, the diode element 116 is compressed by a threaded member 120 into the resonator structure 119. The center frequency of the Gunn diode oscillator is determined by the diameter of the resonator disc 118; minor adjustments to its frequency can be provided by mechanical tuning rod 124. The bias voltage of the InP Gunn diode can be varied in order to transmit millimeter wave energy at frequencies varying by approximately $\pm$300 MHz at 95 GHz. If needed, additional tuning can be provided by introducing a dielectric material such as sapphire into the vicinity of the resonant disc 118. Typical continuous-wave radiative power levels for the device are 100 mw/emitter at 95 GHz. As noted, normal manufacturing tolerances on the components of these oscillators ensure that their resonant frequencies will vary sufficiently that an array of such sources will emit essentially incoherent radiation, as required according to one aspect of the invention. This is very convenient; by comparison, rather elaborate measures

would be r quired if it were desired that the sources be coherent (i.e., all oscillate at the same frequency) as suggested by some of the prior art.

As discussed above, it is also possible to form the millimeter wave sources on the same substrate as the radiating antenna elements. Such microwave integrated circuit (MIC) devices, which are shown in Figs. 17 and 18, may prove economically preferable to those shown in connection with Figures 13 and 14 in a number of applications.

An MIC millimeter wave oscillator (Fig. 17) typically utilizes a discrete-package Gunn diode device mounted on a conductive base plate which supports a dielectric substrate on which the printed circuit components of the oscillator are formed. See generally, Rubin, "Varactor-Tuned Millimeter-Wave MIC Oscillator", IEEE Trans. on Microwave Theory and Techniques, 866-867 (Nov. 1976).

There are three essential planar components of each MIC oscillator:

(1) A resonator, to establish the operating frequency;

(2) A bias network, to provide DC voltage to the diode, without interfering with the oscillator operation; and

(3) An output network to extract the power from the Gunn diode and match the impedance of the load circuit.

Figure 17 shows a number of different resonant circuit geometries in configurations which may be appropriate in various circumstances. Typically a planar resonator is formed which comprises a conductive member having a dimension equal to one-half or one full wavelength at the intended operating frequency of the device. The resonator in conjunction with the Gunn diode establishes the operating mode and operating frequency of the oscillator. Variations in these devices according to manufacturing tolerances, etc., from one oscillator to the next, provide sufficient variation in their resonant frequency to ensure that the illumination provided by them is non-coherent, as required according to one aspect of the invention. Again, this is obviously very convenient; the oscillators can simply be permitted to radiate at their resonant frequencies.

The bias network typically comprises a low pass filter of alternating high and low impedance transformer sections, each being approximately one-quarter wavelength long. The output network consists of a power coupling arrangement for coupling a "microstrip" transmission line to a suitable antenna. Where the antenna is also planar, for example when a transmitting antenna similar to the receiving antenna discussed above in connection with Figures 4 and 5 is used, no coupling structure per se is needed, and the antenna elements can be formed directly on the same substrate as the oscillator itself.

Figure 17(a) shows such an assembly. The antenna elements 200 and 202 of the oscillator are essentially similar to those discussed above in connection with Figures 4 and 5. Large numbers of these assemblies can be formed on a single substrate, and plural substrates

mounted parallel to one another, in the manner of Figure 4, to form a multiple-element source of linearly-polarized millimeter-wave local oscillator and/or illumination energy. The plural substrates can also be mounted on a flat panel.

The oscillator section 204 comprises a conductive resonator 206 formed on a dielectric substrate 208. A Gunn diode 198 is assembled to the resonator 206 in a manner discussed below in connection with Figure 18, which is a cross-section taken along the line 18-18 of Figure 17(a). The bias network comprises enlarged conductive areas 210 connected to the resonator 206; these comprise an RF filter choke which prevents the microwave energy from propagating toward the positive bias voltage connection, which is indicated at 212. Negative bias is provided to the conductive block on which the circuit is formed, as indicated in Figure 18. Amplitude modulation of the output millimeter-wave energy is accomplished simply by modulation of the bias voltage.

An output structure comprising a conductor indicated at 214 couples the oscillator to the paired conductive elements 200 and 202 of the antenna. The conductor 214 extends over the ends of the conductive elements 200 and 202, and is spaced from them by the dielectric substrate 204 (see Fig. 18). The end of the conductor 214 extends past the slot between the conductive elements 200 and 202 a distance equal to the operating wavelength of the system divided by four, and the end of the slot extends a similar distance past the conductor 214, as indicated.

Figures 17(b) - (e) show alternative embodiments of the oscillator structure. Those shown in Figures

17(b) and (c) include circular resonators 220, and semicircular RF choke elements 222; the operation of these devices is essentially similar to that of Figure 17(a). The principal resonant mode of the circular oscillator is circular, while the rectangular resonator 206 shown in Figure 17(a) has a linear principal oscillation mode. The circular oscillator 220 is coupled to the antenna elements similarly to that of Figure 17(a), as indicated by the dotted lines. Figures 17(d) and (e) show alternative arrangements of a millimeter-wave source having a rectangular resonator, as shown in Figure 17(a). The selection between these alternative constructions can be made in accordance with well-understood engineering principles and according to the desired layout of the device on the circuit substrate.

The millimeter-wave oscillators shown in Figures 17(a) - (e) may also be employed to drive a waveguide-type transmitting antenna, if desired. In such case, the end of the network output lead 214 can be simply extended endwise through a slot in one wall of a rectangular waveguide, that is, into its interior cavity. The plane of the planar network output lead 214 lies along the axis of the waveguide, and parallel to two of its walls.

Figure 18 shows, as mentioned, a cross-sectional view along the line 18-18 of Figure 17(a), that is, through the actual diode structure itself. The conductive resonator 206 is disposed on the dielectric substrate 204 which in turn is disposed upon a heavy brass block 246. A standard Gunn diode package, comprising a diode chip 248 on a conductive pedestal 224 formed integrally with a threaded conductive heat sink member 226, is threaded into the block 246 by way

of intermediate bushing member 228. The bjective of this structure is to provide a high heat sinking capacity to the chip 248. The chip 248 is connected by plural bonding wires 230 to a diode cap 232 which is soldered as indicated at 234 to the resonator 206. Plural leads 230 are provided to reduce the impedance of the connection between the diode cap 232 and the chip 248. The spacing of the cap 232 from the ground plane established by the block 246 is defined by the threaded heat sink 226, and is important to reduce the shunt capacitance of the structure. An alumina spacer ring 240 separates the diode cap 232 from the threaded heat sink member 226 by the proper distance.

Bias voltage is supplied as indicated at 242 to drive the diode and cause it to oscillate at its resonant frequency. The bias voltage can be modulated to provide amplitude and/or frequency modulated output millimeter wave energy, as mentioned above. In general, each of the elements of the sources will be modulated identically.

As indicated above, there are engineering tradeoffs to be made in the selection of a millimeter wave energy source, and in particular, between the integrated circuits shown in connection with Figures 17 and 18 and the waveguides shown in connection with Figures 13 and 14. Hybrid structures using the Fig. 17 oscillator with waveguide rather than planar antennas are also feasible. At present, conventional waveguide Gunn diode oscillators as shown in Figures 13 and 14 are more expensive but provide higher output levels than the integrated circuit devices currently available. The applicants believe, however, that ultimately the integrat d circuit devices described in connection with Figures 17 and 18 will be sufficiently

powerful to be used in most of the applications for the present invention discussed in this specification. Furthermore, the production cost of the planar integrated circuit devices is sufficiently low, compared to the three dimensional waveguide devices of Figures 13 and 14, that the integrated circuit devices can economically be multiplied to yield any desired output power level. Savings in space and weight are also expected to be realized by employment of the planar construction shown in Figures 17 and 18. As mentioned, other sources of radiation are within the scope of the invention where functionally equivalent. Specifically, the individual sources of millimeter wave energy employed according to the preferred embodiment of the invention provide linearly polarized energy; the energy provided by any such source is normally at substantially a single frequency.

Selection of an operating wavelength and frequency for the system according to the invention involves several design tradeoffs. Aperture size is reduced for smaller wavelengths, encouraging miniaturization of antenna components, but mixer performance decreases at the higher frequencies concomitant with smaller wavelengths. At present, the optimum frequency is considered to be 94 GHz (3 mm wavelength) or 140 GHz (2 mm), but this could change as better components (principally mixers and sources) become available or are invented.

Figure 15 shows a cross-sectional view through one of the mixer diodes 80 which are preferably formed directly on the substrate 70 on which are formed the conductors 68 making up each of the antenna elements 66. In this embodiment, the diode 80 comprises bonding pads 84 and 85 which may be f rmed of gold and ext nd

through vias (that is, through-holes) 86 in a semi-insulating (SI) GaAs substrate 88. The gold bonding pads 84 and 85 contact further additional gold electrodes 90 and 92 formed on the opposite side of the substrate 88. Electrodes 90 and 92 overlay the actual diode structure. The diode structure comprises a first layer 94 of n^+-GaAs which is in contact with the semi-insulating GaAs substrate 88. Over this is formed an n-GaAs layer 96. Atop this layer 96 is provided a layer 98 of Schottky metal, which in a preferred embodiment may be Ti/Pt/Au. The Schottky metal layer 98 is directly in contact with electrode 92 and is thus in contact with bonding pad 84. The n^+-GaAs layer 94 is in contact with the other electrode 90 and thus the other bonding pad 85 via an ohmic layer 93 of AuGe/Ni. Finally, an insulating/ passivating SiO_2/Si_3N_4 material fills spaces 100 and 102 between the various layers. In a particularly preferred embodiment, the spaces 100 and 102 may also include an air gap between the electrode 92 and the GaAs layers 93 and 94, i.e., around the Schottky metal 98, with or without the SiO_2/Si_3N_4 material. This has the beneficial effect of reducing the parasitic capacitance of the mixer diode 80.

It will be appreciated that the structure described lends itself to ready fabrication directly on the substrate 70 carrying conductors 68 of the mixer/detector assembly, particularly as compared with a process involving assembly of conventional discrete diode elements, e.g., vertically-oriented or planar beam-lead diodes to the electrodes.

Ultimately, and subject to further developments in semiconductor materials and fabrication techniques, it may be possible to integrate the function of

amplifiers 82 with that of mixer/detector diodes 80. This would require the development of amplifiers capable of operation at millimeter-wave frequencies. It is envisioned that such devices could perform the mixing and amplification functions within a single semiconductive element. This would be highly desirable, as it would presumably substantially increase the signal-to-noise ratio of each mixer/detector element 66. The claims of this application are intended to include such improved devices, when they become available.

The components of the contraband detection system of the invention having been disclosed in detail, certain of its aspects and the improvements it provides can now be better understood. It will be appreciated that there has been described a millimeter wave contraband detection device which comprises a "staring" array of mixer/detector elements which does not require mechanical or electronic scanning in order to provide an image of an entire field of view. Instead, at all times, the output signal from each of the antenna/detector elements of the array 36 is mapped uniquely to a portion of the device's field of view. For this reason, according to an important aspect of the present invention, it is not necessary that a detecting device be mechanically scanned with respect to the field of view, or that the sources be scanned, in order that a complete image can be generated, as in all proposed prior contraband detection systems employing millimeter waves. Instead, the detectors each respond to millimeter wave energy from a portion of the field of view. This greatly simplifies generation of an image of objects in the field of view, and allows doing so essentially in real time.

Similarly, according to the invention, the entir field of view can simply be illuminated uniformly by a number of spatially distributed quasi-coherent sources, each formed of a plurality of individually coherent sources. The spatial distribution eliminates "glint", while the avoidance of coherent illumination eliminates "speckle". The oscillators are permitted to radiate at their respective resonant frequencies; manufacturing variations will be sufficient to ensure that coherency is avoided in a simple, elegant, and economical manner.

Moreover, it will be appreciated that in the preferred embodiment, the individual elements of the array providing the local oscillator signal are mapped directly to a corresponding portion of the detector array. The detector array is thus evenly illuminated by the local oscillator signal, which is highly desirable. Further, when the same source is used to illuminate the field of view, this results in the same gain being applied to all elements of the signal, greatly simplifying signal processing.

The millimeter wave sources and detectors of the invention which can be used for interdiction of drug trafficking or for detection of plastic or ceramic weapons not readily detectable or discernable by x-ray or magnetic detectors rely in part on the fact that the polarization of electromagnetic waves is randomly rotated to a degree by amorphous dielectric materials. According to the invention, the system operating parameters are optimized in accordance with the material to be detected, and the background return signal to be avoided. As discussed above, the ceramic and plastic materials now finding increasing use in weapons are best detected according to applicants' invention if the plane of polarization of the radiation

emitted by the sources is orthogonal to the polarization of radiation to which the detector arrays are preferentially sensitive.

According to another aspect of the invention, as discussed above, the polarization of the illumination relative to that of the detectors can be varied. For example, one or the other can be effectively rotated or varied over time for detection of metallic weapons (where the planes of polarization should be parallel) and for detection of plastic or ceramic weapons (where the planes of polarization should be orthogonal).

Conventional target detection systems involving detection of reflected radiation, e.g. radar systems, rely principally on retroreflection, in which radiation is reflected from the target back directly at the source. For this reason, radar reflectors comprise "inside corners" from which a direct reflection can usually be detected; for the same reason, the so-called Stealth aircraft design avoids sharp corners between flat surfaces. Retroreflection commonly involves a number of reflections from flat, uniformly reflective surfaces. The electric field vector of the reflected radiation experiences a 180° phase change upon each such reflection, which is equivalent to a 180° rotation of the plane of polarization. Therefore, in order to optimize detection, the plane of preferential sensitivity of the detector is conventionally aligned parallel to the plane of polarization of the illumination radiation.

According to the present invention optimal detection of plastic, ceramic and other amorphous dielectric objects (such as bags of narcotic powder) is obtained when the plane of prefer ntial sensitivity of

the detector array is <u>orthogonal</u> t the plane of polarization of the incident radiation. (As above this is referred to herein as the "orthogonal arrangement" of the system of the invention.) This arrangement is therefore contrary to the accepted practice for detecting radar targets. Applicants believe that the orthogonal arrangement is effective because amorphous materials reflect the polarized radiation more or less randomly, such that a detectable fraction of it lies in the plane of preferential sensitivity of the detector, which according to the orthogonal arrangement then is able to provide adequate contrast in the received signal.

Furthermore, by use of the orthogonal arrangement, detection of reflection from specular metallic surfaces is reduced for the reasons noted above, that is, the detectors are arranged to reduce their sensitivity to radiation from specular metallic objects. This further increases the effective signal-to-noise ratio for radiation reflected from the amorphous ceramic and plastic objects.

Finally, it appears that reflection of radiation from flesh and clothing does not alter its polarization appreciably, so that it does not contribute significant noise to the signal detected in the orthogonal arrangement of the system.

As noted, metallic weapons and other objects can still be detected using the system of the invention in the orthogonal arrangement, because they normally comprise surfaces which are not flat (e.g., trigger guards, grips, and the lines along which the external planes of their barrels meet). Random reflections or "scattering" from these surfaces can be detected by the

system in its orthog nal arrangement. Such bj cts show up as points of reflectivity on a video imaging system, and are readily identifiable by operators.

More specifically, according to one aspect of the invention, polarized radiation is used according to the invention to illuminate the objects to be examined because the "reflection history" of polarized radiation can be determined upon detection of the reflected radiation. In the linear-polarization case, as discussed above, the plane of polarization of the radiation remains unchanged upon reflection from specular metallic surfaces, but is varied randomly upon reflection from and scattering within amorphous objects. Specifically, the polarized radiation undergoes varying multiple internal reflections, as well as scattering from external features, leading to random superposition of changes in the plane of polarization, upon reflection from such amorphous objects. The linearly polarized radiation reflected from metallic objects can be removed from the detected signal by disposing the detectors orthogonal to the plane of polarization of the radiated reflection. A polarizing grid can be employed to further filter out the unwanted signal component. The signal which remains to be detected is therefore principally radiation reflected from the amorphous objects.

In the Hodges <u>et al</u> report discussed above, it was noted that certain plastic explosive materials ("plastique") could not be detected using the system there described. These materials can be detected using the system of the invention because during manufacture the material is stressed, so as to leave stress lines which serve as internal scattering centers. Objects made of these materials thus show stress lines when

imaged using the system of the invention. [It will be appreciated that plastic models of structures are commonly built and photographed under polarized light to analyze the stress patterns. The polarized radiation is scattered from the internal structure of the plastic in a manner which varies according to the stress on the object. A similar scattering mechanism is used according to this aspect of the invention.] This is a somewhat different scattering mechanism than that responsible for detection of materials such as bags of powder. Molded objects such as ceramic or plastic handguns may exhibit both scattering mechanisms.

The same property of preserving the reflection history may be useful in embodiments of the invention employing radiation exhibiting other polarization characteristics, by discriminating radiation reflected from metallic surfaces (again, which involves a predictable phase change of the electric field) from radiation randomly affected upon reflection from amorphous objects.

It was mentioned above that the linearly polarized radiation used in the preferred embodiment of the invention is a special case of the more general elliptically polarized radiation. Elliptically polarized radiation could also be used for contraband detection according to the invention, as could circularly polarized radiation, another special case. For example, linearly polarized transmitted radiation can be converted to circularly-polarized form using a quarter-wave plate, as discussed in connection with Figure 11. The "handedness" of the radiation changes uniformly upon reflection from metallic surfaces, while the circularly polarized radiation can be expected to

b reflected m re randomly from amorphous objects. Th circularly-polarized radiation received at the detector can similarly be converted to linearly-polarized radiation by a second quarter wave plate. The polarization of this radiation will correspond to the "handedness" of the received circularly polarized radiation; the orientation of the detector array can then be employed to detect the handedness of the detected radiation. However, radiation reflected by metallic and amorphous objects will normally both contain radiation of both handednesses. For this reason, orthogonal orientation of the sources and detectors may <u>not</u> be sufficient of itself to discriminate between the reflecting objects as in the case of linearly polarized radiation, which is used in the preferred embodiment of the invention. However, in certain circumstances, elliptically or circularly polarized radiation may be highly useful for contraband detection using the system of the invention.

As an alternative to using quarter-wave plates to transform linearly polarized radiation to circularly polarized radiation at the source and to perform the inverse transformation at the detector, sources and detectors of circularly-polarized radiation may be employed. These could comprise spiral conductors formed on substrates perpendicular to the optical axis of the system. Diode oscillators and mixers would be located at the center of the respective spirals to perform the same functions discussed above. Ground planes on the rear of the substrates would provide the other terminals of the transmitting and receiving antennas. Through-holes in the substrates would carry power to the transmitting antenna and the signal from the detector diode. The handedness of the transmitting antenna's spiral determines the handedness of the

transmitted radiation, and the detection antenna will preferentially detect radiation of the opposite handedness, i.e., of the orthogonal polarization, if aligned in the opposite orientation. Alternatively, special feed arrangements to square or rectangular patch antennas disposed on a planar substrate perpendicular to the optical axis of the system can be used to generate or receive circular polarization.

As mentioned, it will be recognized that both linear and circular polarization are special cases of elliptical polarization. Linear polarization is preferred based on practical component availability considerations, and because linear polarization affords, as discussed, a ready and elegant means of eliminating noise due to radiation reflected from clutter, i.e. objects other than contraband, thus improving the signal-to-noise ratio of the signal of interest. Nevertheless, the claims of this application are to be deemed to include radiation polarized other than linearly, unless they are specifically limited thereto.

The system of the invention has principally been discussed in connection with a portal inspection system for control of the access of individuals to secured areas. Other uses for and configurations of the system of the invention will be apparent. For example, the presence of a quantity of marijuana in a bulk dielectric material, such as a bale of some other vegetation, could be detected by placing a millimeter wave source on one side of the bale and a detector on the other. Unless the dielectric constant of the marijuana were somehow made precisely equal to that of the vegetation, a detectable variation in transmission strength would occur, indicating that the material was

not homogeneous. An imaging device could be arranged to display the relative position of the material within a larger quantity of vegetation. In the same manner, large quantities of dielectric materials could be inspected for the presence of weapons, contraband, and the like. Such a system, used in either the transmissive or reflective mode, could be used to inspect the holds of grain-carrying ships and the like. Sources and detectors according to the invention could be provided on either side of airline conveyors carrying passenger baggage for its inspection.

The basic system components provided according to the invention, that is, the millimeter-wave imaging "technology" of the invention, having thus been described in detail, some of the applications of this technology and these components to particular problems can now be discussed.

As indicated in several examples above, a principal object of the invention is to provide a real time imaging system for use in aircraft applications to provide an image of a runway despite the presence of atmospheric constituents such as fog, snow, blowing sand or dust, chemical gases, and the like. In the first embodiment of such a system, an airplane can simply be fitted with a radiometric millimeter wave detector array, preferably the superheterodyne type illustrated in Figure 4, in which a local oscillator signal is employed to increase the signal-to-noise ratio of the array. Such a system can provide a video image of the field of view, e.g., up to several miles ahead of the aircraft. In a noncombat situation, that is, wh re there is no detriment to transmitting millimeter wave energy from th aircraft, the Figure 5 embodiment of the system of the invention can be

employed, in which the oscillator used to provide the local oscillator signal is also used to illuminate the field of view. Millimeter wave "landing light" sources can also be mounted on the airplane wings to illuminate the field of view.

In a particularly preferred embodiment of this system, millimeter wave runway lights comprising millimeter wave sources as described above are provided in positions on the airport corresponding to those in which colored runway lights are now disposed. The millimeter wave energy emitted by these runway lights can be modulated to be encoded, which would enable processing electronics aboard the airplane to distinguish one type of runway light from another. A head-up display can then be provided to the pilot, using this information to provide colored symbols corresponding to those normally seen by the pilot on landing visually. The modulation signal provided to the millimeter wave landing lights can be a simple sine wave of a predetermined frequency, an on/off binary code, or any other known code suitable for modulation of a continuous-wave (CW) signal. Reflectors of millimeter wave energy (simply comprising metal corners as in the case of conventional radar reflectors) could be disposed on the runway, to define highly reflective and hence readily visible positions on the airfield.

Another application of the technology provided according to the invention is that of rescuing downed airmen or capsized sailors. There are now available emergency position indicating beacons (EPIRBs) which transmit at radiofrequencies when the beacon hits the water. These provide a "fix" to a suitable radiofrequency detector, but the wavelengths of the

radiofrequency signals ar so l ng that accurat position indication cannot be derived. Accordingly, present day EPIRBs are suitable only for bringing a rescue craft into the vicinity of the individual; visual observation must then be made in order to actually effect the rescue. Rescue in fog is then hindered.

According to the invention, an EPIRB may be provided with a millimeter wave source as well. Since millimeter waves have substantially shorter wavelengths than radio waves, the corresponding millimeter wave detecting array is suitable to produce an image indicating the precise position of the beacon of the individual to be rescued. It is envisioned that such a system would be sufficiently accurate to enable a helicopter to directly approach a downed airman or capsized sailor and lower a life jacket or the like directly from above, even in visually impenetrable fog. In this case, the Figure 7 superheterodyne receiver array would normally be used; use of the millimeter wave emitting beacon would eliminate any need to illuminate the scene and betray the presence of the rescue craft.

More broadly still, the invention contemplates provision of a millimeter wave source wherever a light is now installed to permit night-time use of a transportation facility, together with an image display device on the corresponding vehicles. In an airport, for example, runway approaches, runways themselves, taxiways and docking areas would all be provided with millimeter wave sources which would be encoded (again, by modulati n f millimeter wave radiation) such that a video display provided the pilot could be false-colored

to correspond to the n rmal colors of these lights under clear sky conditions.

Similar applications for the technology provided according to this invention exist in ship berthing lights, ship running lights, and obstruction warning lights placed at the tops of buildings and bridges, and on lighthouses and other navigational aids, such as channel markers in waterways. In general, in any application where a visible light is provided presently to allow operations at night and wherein atmospheric constituents such as fog, snow, blowing sand or dust, etc. now interfere with such operations, a millimeter wave source can be provided. A corresponding millimeter wave detector can be added to the vehicle or other operational entity (such as a stationary traffic monitoring imager, for use by an air traffic controller, for example) to enable safe operation even in the presence of such atmospheric constituents.

For example, oil drilling rigs are essentially completely dependent on helicopters for personnel movement. Fog, snow, and rain are common in the North Sea, for example, and very substantially impede these operations. Simply fitting the drilling rigs with millimeter wave beacons and the service helicopters with millimeter wave imaging systems according to the invention, for example, employing the Figure 7 superheterodyne array, would substantially reduce interference with such operations caused by fog and the like. The same of course would be true for other heliports.

The fact that millimeter waves in certain frequency bands are attenuated by the atmosphere can also be used to advantage. For example, one

disadvantage f using a millimeter wave beacon as a runway light on an aircraft carrier would be that this would provide a millimeter wave emission which could be detected by a combatant. By designing the millimeter wave source to operate in a region of relatively high atmospheric attenuation, e.g., at 120GHz, the range of the millimeter wave radiation emitted thereby would be limited to a few kilometers. This would not interfere with normal landing applications, since pilots returning to their ship would know to within a few kilometers where it was, so that this limited range would be adequate for effective landing assistance. The same considerations would apply to using millimeter wave beacons to define a temporary landing field without revealing its location to combatants monitoring millimeter wave frequencies.

Other applications of the millimeter wave imaging technology described in this application will occur to those of skill in the art. As indicated above, substantially any imaging application in which atmospheric constituents obscure visible or infrared transmission can proceed regardless through the use of millimeter wave imaging technology. For example, a radiometric millimeter wave imaging system, preferably employing a local oscillator to increase its sensitivity, would be directly applicable to protection of the perimeter of an enclosed area, such as a military installation. The field of view could be illuminated using the Figure 8 embodiment of the invention if need be to ensure an adequate signal-to-noise ratio. Similarly, millimeter wave imaging technology provided according to the invention could be used in various airborne and satellite-borne reconnaissance op rati ns; a principal advantag would

be that clouds and adverse weather conditions would not affect the imaging of the field of view.

The "radiometric" embodiment of the invention shown in Figures 6 and 7, that is, in which the field of view is not illuminated, has the significant advantage in the military context that the imaging system does not emit any radiation which can be detected by a combatant and used to home a missile or other ordnance on the imaging device. This has obvious advantages.

Most of the applications of the millimeter wave imaging technology described above have involved simply generating an image of the field of view which would be comparable to that visible to the eye if the scene were fully lit. According to a further aspect of the invention, and as described in connection with the embodiment of Figure 8, the local oscillator signal can also be time-varied and transmitted into the field of view as an illumination beam. When the illumination beam is reflected from objects in the field of view, information contained in the frequency modulation thereof can be used to derive information concerning the relative position, velocity and range of objects in the field of view.

More particularly, the system of Figure 8 can be employed together with any conventional radar signal processing apparatus and using conventional radar signal wave forms to provide a millimeter wave radar image. This would have applicability to vehicle collision avoidance, in navigation, and in operation of robot armored vehicles, and in other applications which will be apparent to those of skill in the art.

Furthermore, while th invention has been described principally in connection with providing an image corresponding to the field of view of a millimeter wave sensing array, it should be appreciated that imaging per se is not a requirement of all claims of this application. Use of the millimeter wave sensing technology provided according to the invention is considered within its scope even in cases where an image corresponding to the field of view is not made per se, where not excluded by the following claims.

Any of a wide variety of image processing and image enhancement and analysis techniques may be combined with the signal generation and processing techniques according to the invention, such as convolution, false coloration, edge enhancement, contrast enhancement, and identification of individual objects in the image both by comparison to known shapes and otherwise. Note in this connection that the fact that the image signal is provided pixel-by-pixel by the staring array of the invention makes it particularly amenable to many image processing techniques, especially those involving Fourier transformation. Such teachings, which are now or later fall within the skill of the art, are considered to be within the scope of the invention unless expressly excluded by the following claims.

While several preferred embodiments of millimeter wave components provided by the invention have been described above, together with several applications for their use, these should not be considered to limit the invention. The invention is to be limited only by the following claims.

WE CLAIM:

1. Apparatus for detection of contraband, comprising:

at least one array 162 of spatially distributed point sources 112 of millimeter wave radiation, arranged to illuminate a field of view,

means 40 for focusing millimeter wave radiation from the field of view onto a focal plane, and

an array 36 of detectors 66 disposed in said focal plane, each of said detectors generating an output signal responsive to millimeter-wave radiation from a particular portion of the field of view,

whereby said output signals may be provided to means 22 for displaying an image of the field of view, the pixels of the displayed image corresponding to the output signals generated by the elements of the array.

2. The apparatus of claim 1, wherein said sources of radiation 112 comprise oscillators, and the oscillators are not constrained to oscillate at the same frequency.

3. The apparatus of claim 1, wherein said detectors 66 are preferentially sensitive to radiation polarized in a first plane and the radiation emitted by said sources of radiation is linearly polarized in a second plane.

4. The apparatus of claim 3, further comprising means for varying the relative orientation of said first and second planes responsive to the nature of the contraband to be detected.

5. Apparatus for the detection of contraband, comprising:

at least one source 110 of polarized radiation, said source being arranged to substantially uniformly illuminate a field of view with radiation exhibiting a first characteristic polarization;

means 40 for focusing radiation from the field of view onto a focal plane; and

an array 36 of detectors 66 disposed in said focal plane, each detector 66 generating an output signal responsive to radiation from a particular portion of the field of view, said detectors 66 being preferentially sensitive to radiation exhibiting a polarization different from said first characteristic polarization;

whereby said output signals may be provided to means for displaying an image of the field of view, and in which the pixels of the displayed image correspond to output signals generated by the detectors of the array.

6. The apparatus of claim 5, wherein said source 110 of polarized radiation comprises an array of point sources 112 of radiation, all of which are similarly polarized, and wherein said sources of said array each emit radiation at a single frequency, but are not constrained to emit at the same frequency, whereby said radiation illuminating the field of view is quasi-coherent.

7. The apparatus of claim 5, wherein said first characteristic polarization is linear polarization in a first plane.

8. The apparatus f claim 7, wherein said detectors are preferentially selective to radiation linearly polarized in a second plane.

9. A millimeter wave imaging sensor, comprising:

means for focusing millimeter wave radiation onto a focal plane;

an array 36 of detectors 66, each comprising an antenna element consisting of a pair of conductive sensing elements 68, said conductive elements being adapted to detect millimeter wave radiation, and a nonlinear circuit element 80 connected across each pair of conductive elements for rectifying millimeter wave radiation detected by said pair of conductive elements;

said array being disposed in the focal plane of said means for focusing millimeter wave radiation from a field of view onto said array; and

oscillator means 26 for emitting millimeter wave energy and substantically uniformly directing the same onto the array of antenna elements as a local oscillator signal, wherein said non-linear circuit elements 80 mix said local oscillator signal with millimeter wave radiation received from said field of view separately in each of said sensing elements of said array.

10. The sensor of claim 9, wherein said oscillator means 26 comprises an array of individual oscillator elements 112, each arranged to illuminate a portion of said array 36 of detectors 66.

11. The millimeter wave imaging sensor of claim 9, wherein said oscillator means 26 which provides said local oscillator signal additionally supplies

millimet r wave en rgy to said field of view to illuminate the same.

12. The sensor of claim 11, further comprising means 28 for dividing said millimeter wave energy provided by said oscillator means into first and second components, a first minor component 14 being incident on said array as said local oscillator signal, and a second major component 24 being directed onto the field of view as an illumination signal.

13. The sensor of claim 9, in combination with beacon means 1 for emitting millimeter wave energy and thereby illuminating selected portions of the field of view.

14. The combination of claim 13, wherein the millimeter wave energy emitted by said beacon means is encoded by modulation of the emitted energy, and in further combination with modulation image signal processing means connected to said image sensing array for identifying said beacon means.

15. The sensor of claim 9, in combination with means for receiving the signals emitted by each of the sensing elements and for generating a image responsive thereto, wherein each pixel of the image corresponds to one of the elements of the array.

16. The apparatus of claims 1, 5, or 9 wherein the elements of said array of detectors each comprise an endfire traveling wave slot antenna 66 each consisting of one of said pairs of conductive elements 68, and said nonlinear circuit element 80 is connected across said pair of conductive elements.

17. The sensor of claim 16, wherein said nonlinear circuit elements 80 are Schottky barrier diodes.

18. The sensor of claim 16, wherein each antenna element of said array of detectors comprises two planar conductors 73 spaced from one another on a dielectric substrate 70, defining a slot 76 between said conductors generally aligned along the optical axis between said field of view and said detector.

19. The sensor of claim 18, wherein each element comprises an RF choke consisting of one or more slots 78 in each of said planar conductors extending generally orthogonally with respect to said slot 76 between said planar conductors.

20. The sensor of claim 19, wherein the diode 80 of each element is formed on a planar substrate 70 and comprises an active semiconductor member which is contacted by said conductor members, and wherein said conductor members are directly bonded to the planar conductors of the corresponding antenna.

21. The sensor of claim 9, wherein the frequency of said energy emitted by said oscillator means is time varied, and said array is connected to means 22 for processing the signals provided by each of the sensing elements to provide an image of the field of view which includes information responsive to the relative direction, range, and velocity of objects in the field of view which reflect the energy emitted by said oscillator means.

22. A system for providing a millimeter wave image of a field of view, comprising:

a millimeter wave imaging sensor, comprising an imaging array 36 of sensing elements, each comprising an antenna 66 comprising a pair of conductive elements 68 sensitive to millimeter-wave radiation, and a non-linear circuit element 80 coupled thereacross, and means 40 for focusing millimeter wave radiation reflected by or emitted from objects in the field of view onto said elements of said array;

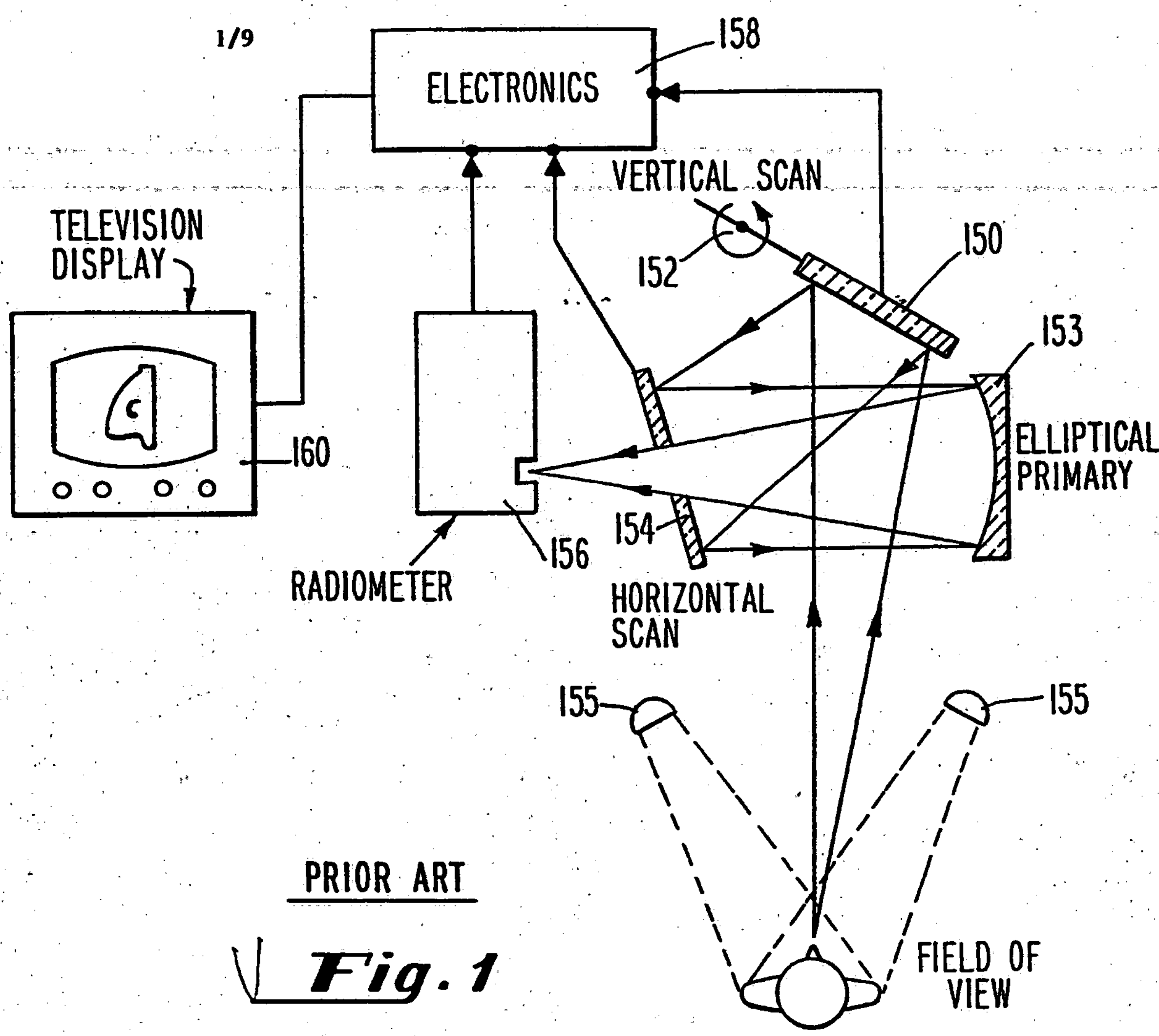
at least one source 26 of millimeter wave radiation for illuminating objects in said field of view for detection by said array; and

image signal processing means 22 for generating an image responsive to millimeter wave energy detected by said imaging elements of said array, wherein each pixel of said image is responsive to the signal provided by one of the elements of said array.

23. The system of claim 22, further comprising oscillator means for providing a local oscillator signal mixed with said detected energy by said non-linear circuit elements 80 in each of the elements of said array, to improve the signal-to-noise ratio thereof.

24. The system of claim 22, wherein said source 26 for illuminating objects is an array of sources 112, and wherein each said source 112 provides a local oscillator signal which is mapped onto a portion of said imaging sensor array corresponding to the portion of said field of view illuminated by the same source of radiation.

1/9



PRIOR ART

Fig. 1

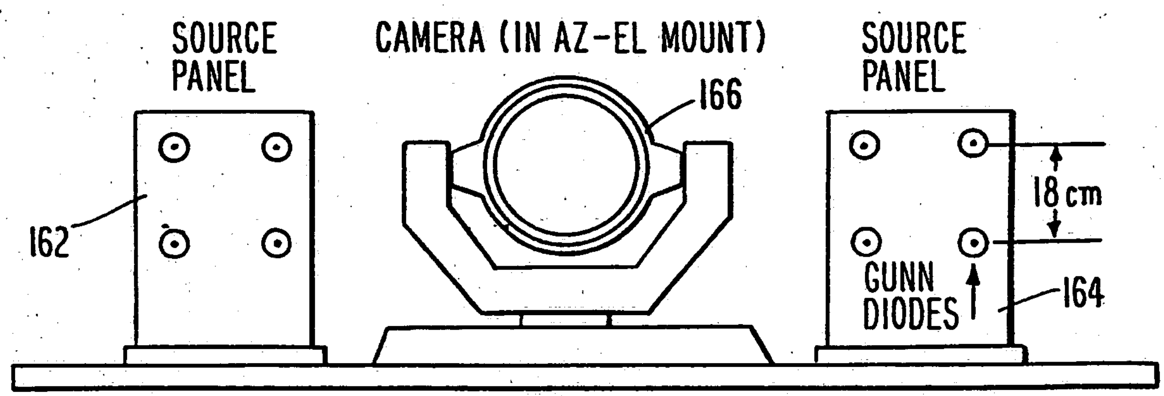
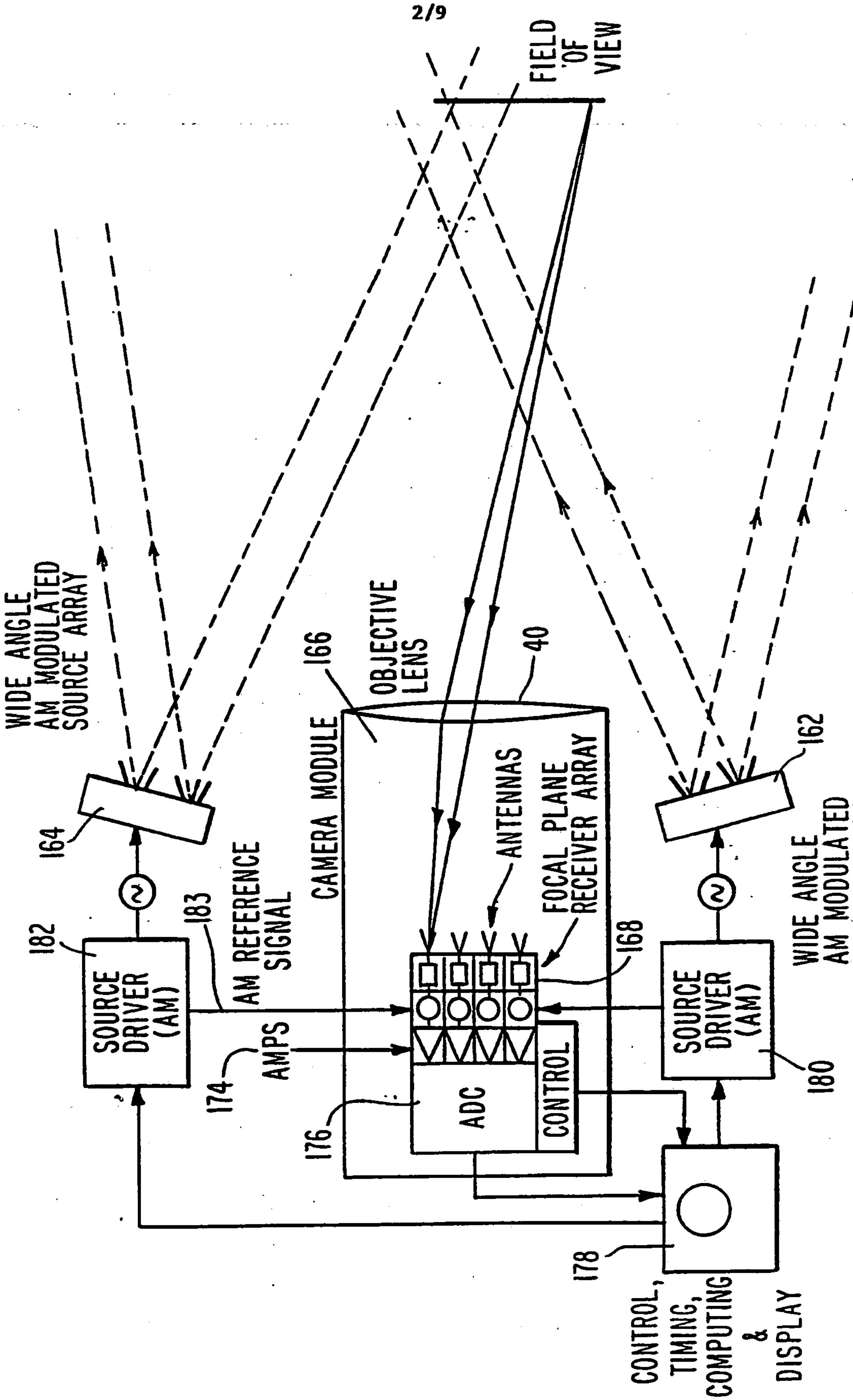


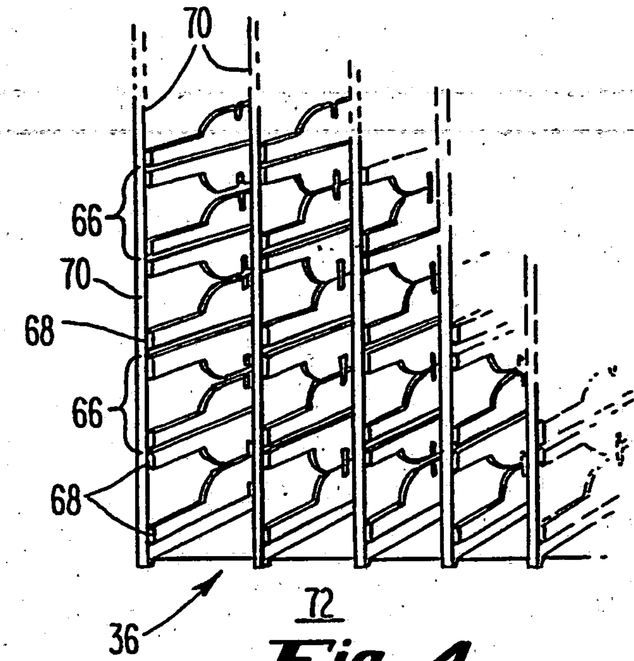
Fig. 3

2/9



FIELD OF VIEW
WIDE ANGLE AM MODULATED SOURCE ARRAY
166
OBJECTIVE LENS
40
CAMERA MODULE
ANTENNAS
FOCAL PLANE RECEIVER ARRAY
162
164
WIDE ANGLE AM MODULATED SOURCE ARRAY
182
183
AM REFERENCE SIGNAL
SOURCE DRIVER (AM)
168
SOURCE DRIVER (AM)
AMPS
174
ADC
CONTROL
180
176
178
CONTROL, TIMING, COMPUTING & DISPLAY

Fig. 2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66
70
68
66
68
36
72

Fig. 4

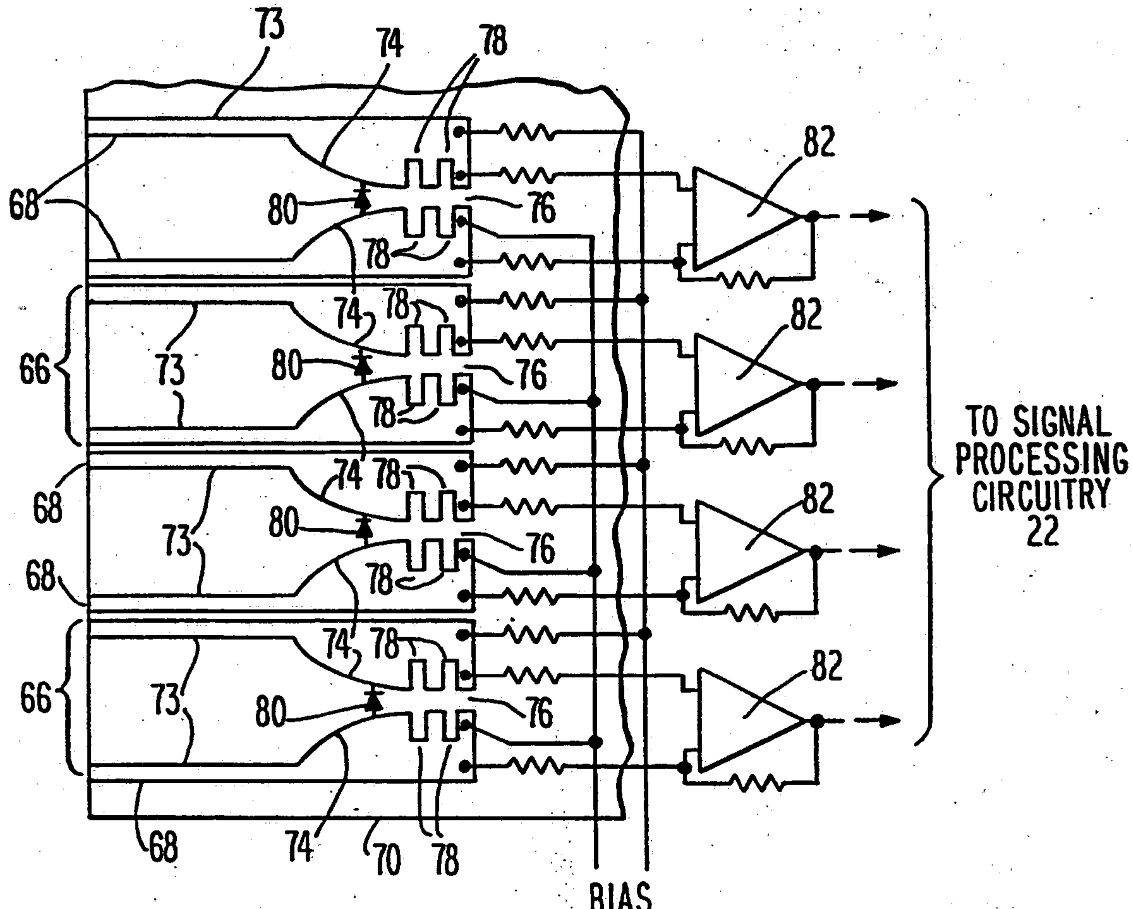

73
74
78
68
80
76
82
66
73
82
68
68
66
TO SIGNAL PROCESSING CIRCUITRY 22
68
74
70
78
BIAS

Fig. 5

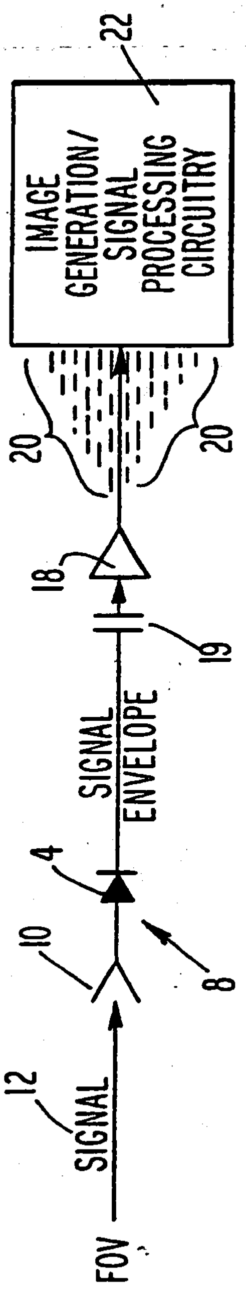


Fig. 6

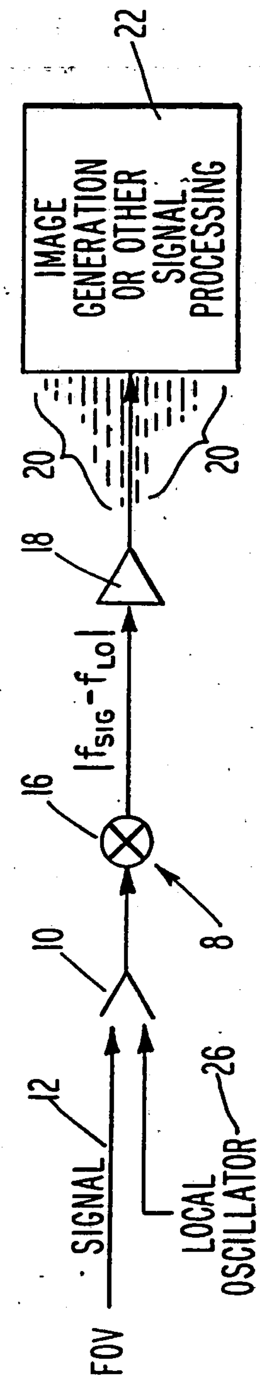


Fig. 7

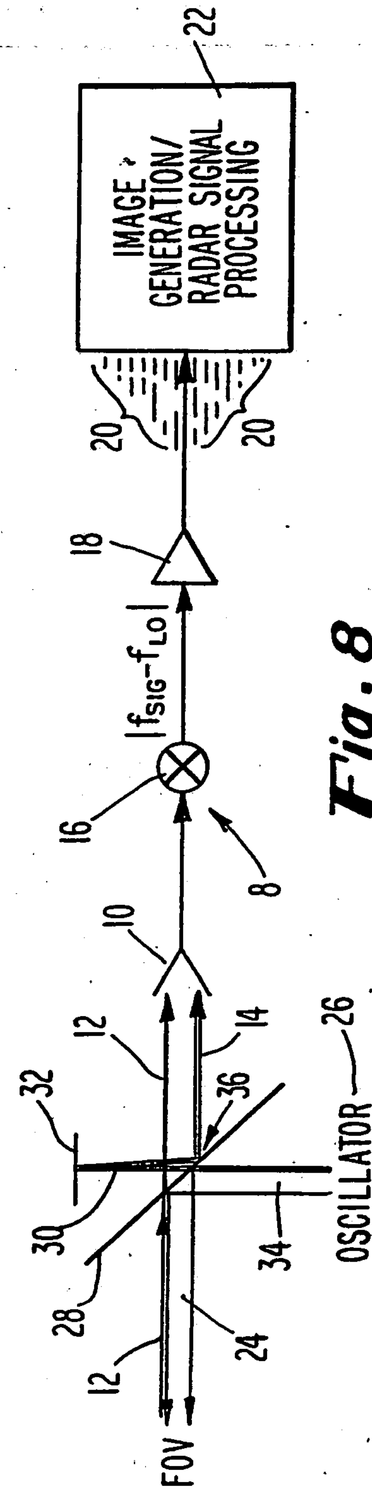


Fig. 8

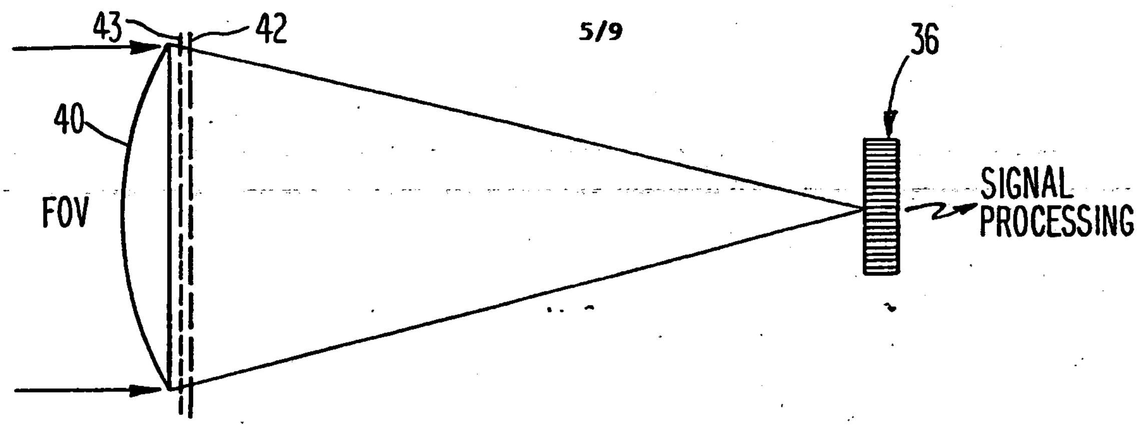


Fig. 9

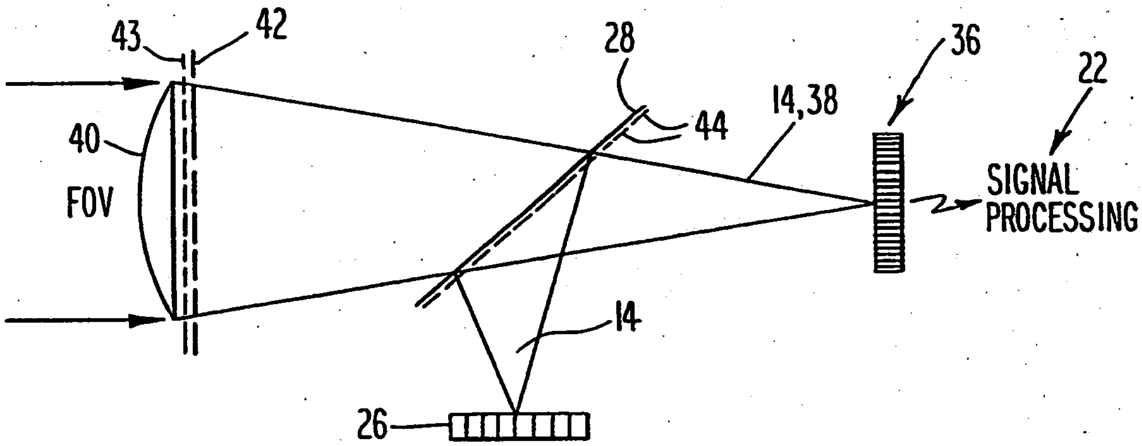


Fig. 10

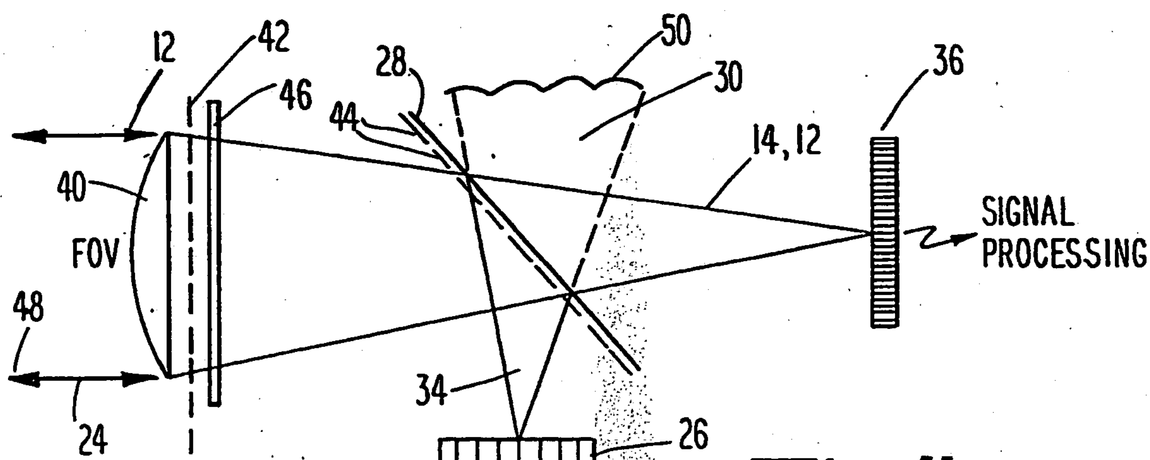


Fig. 11

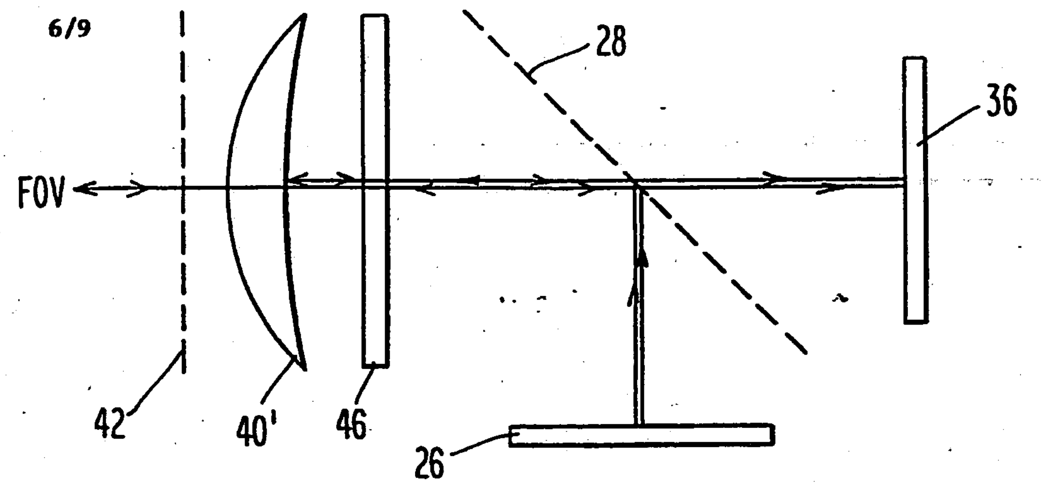


Fig. 12

Fig. 13

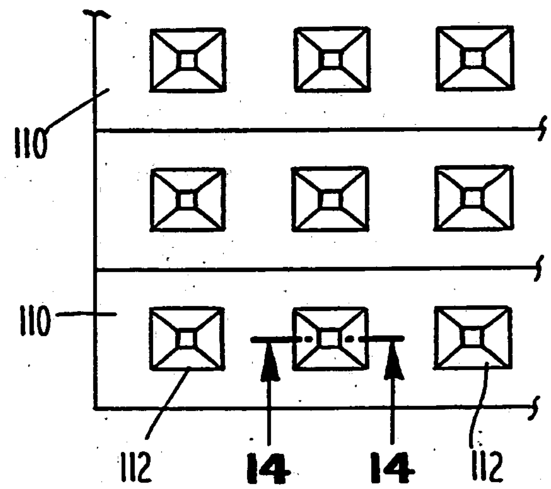
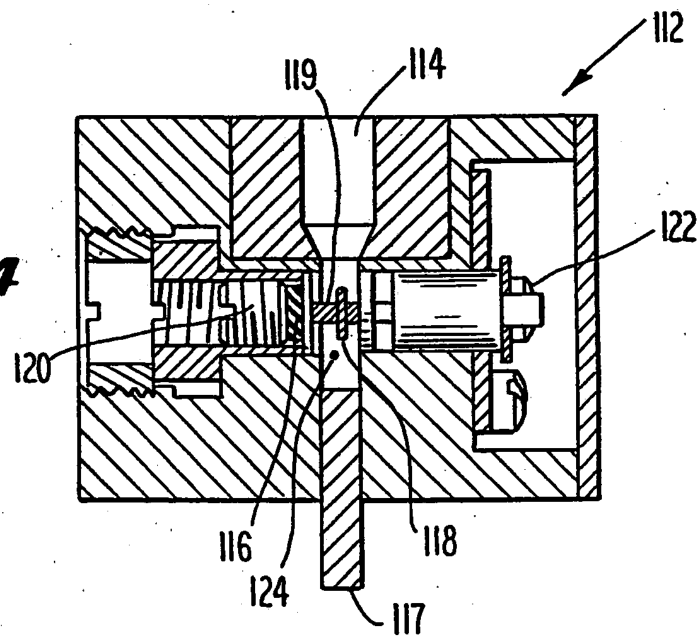
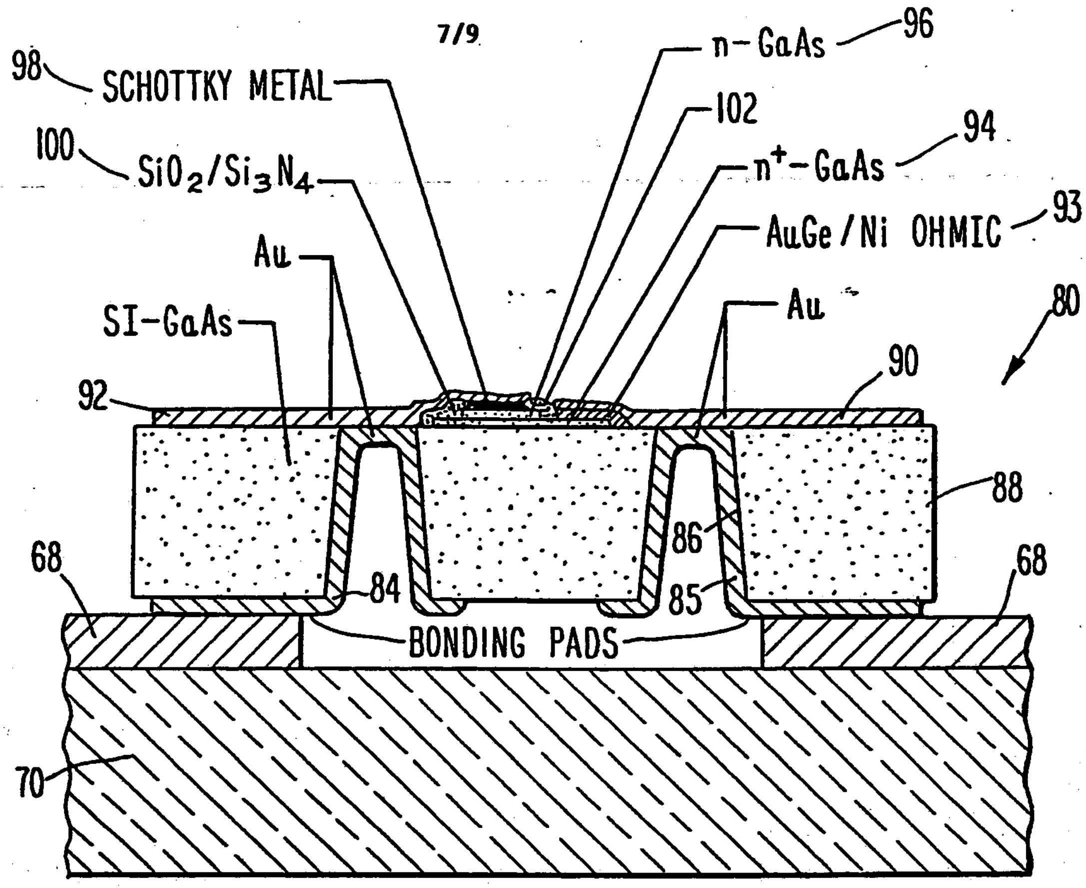


Fig. 14

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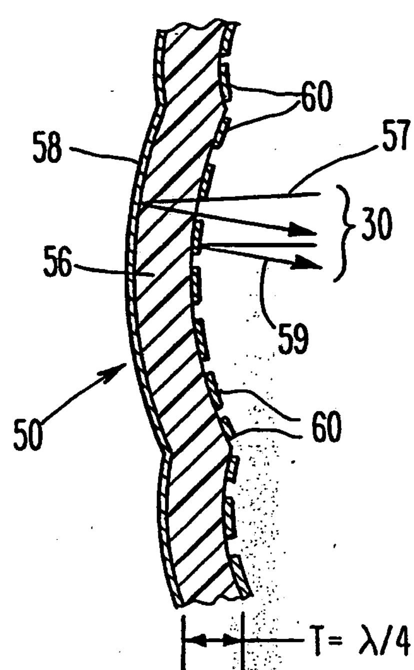
100 SiO_2/Si_3N_4
n-GaAs 96
102
n^+-GaAs 94
AuGe/Ni OHMIC 93
Au
SI-GaAs
Au
80
90
92
88
86
68
84
85
68
BONDING PADS
70

Fig. 15

Fig. 16


60
58
57
30
56
59
50
60
T= λ/4

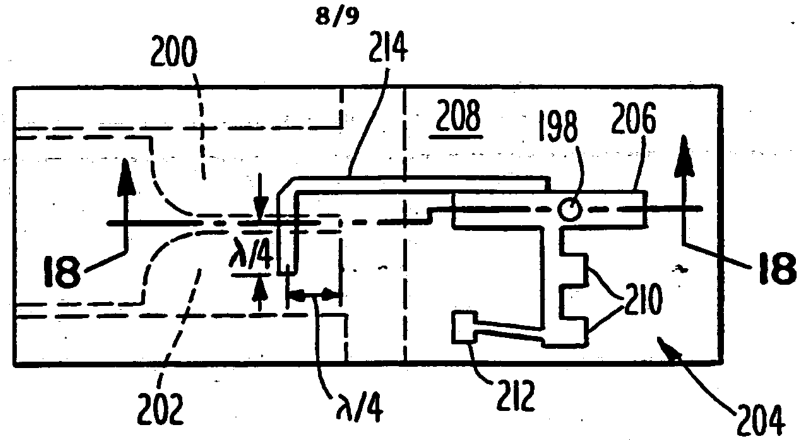


Fig. 17a

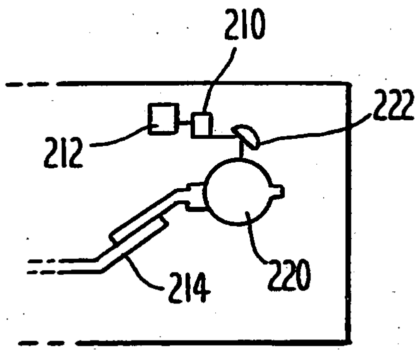


Fig. 17b

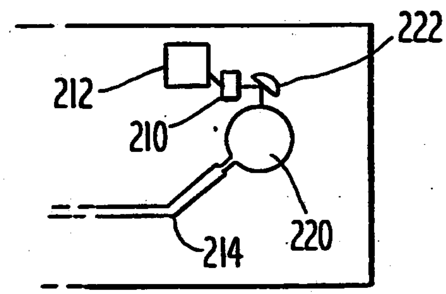


Fig. 17c

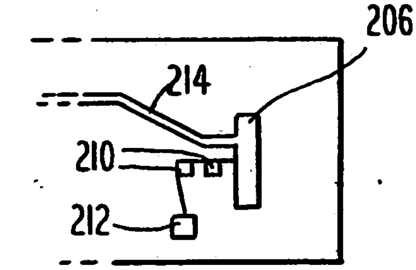


Fig. 17d

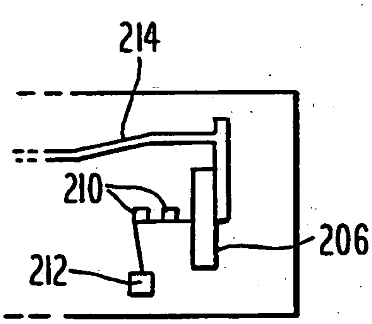


Fig. 17e

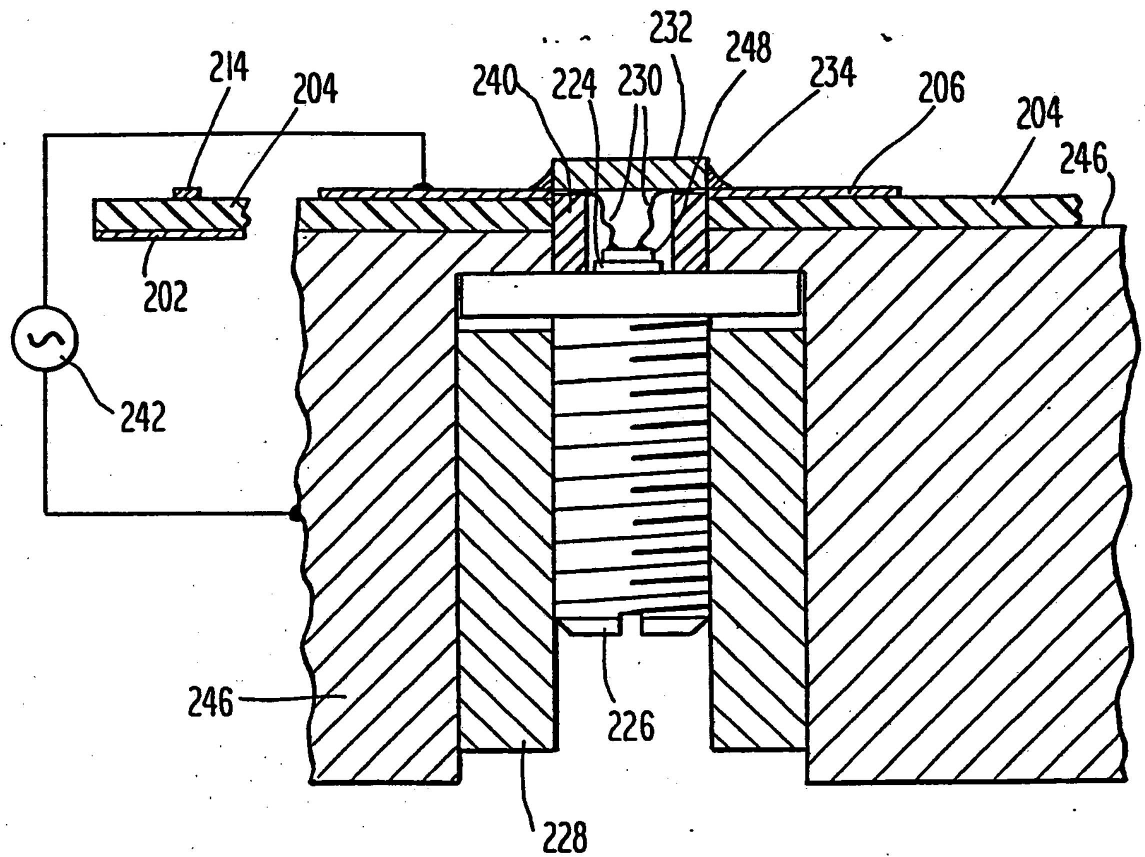


Fig. 18

INTERNATIONAL SEARCH REPORT

International Application No. PCT/US89/03421

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all) [6]

According to International Patent Classification (IPC) or to both National Classification and IPC

IPC 5: G01S 13/89, H01L 27/14 US 342/179; 250/332
342/351;

II. FIELDS SEARCHED

Minimum Documentation Searched [7]

Classification System	Classification Symbols
US	342/179, 351; 356/5,28.5 250/330, 332, 334

Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched [8]

III. DOCUMENTS CONSIDERED TO BE RELEVANT [9]

Category *	Citation of Document, [11] with indication, where appropriate, of the relevant passages [12]	Relevant to Claim No. [13]
X Y	Korzeniowski et al, "Imaging System at 946HZ Using Tapered Slot Antenna Elements," Eighth IEEE International Conf. on Infrared and Millimeter Waves (1983) Figs 1+2, pg. 1, col. 1, 2nd par., col. 2, 3rd par.	1,22,23 9,13,14,15,16/1, 16/9,17-20
X Y	Yngvesson et al., "Millimeter Wave Imaging System with an Endfire Receptor Array," Tenth International Conf. on Infrared and Millimeter Waves (1981) Fig. 7, 2nd pg. 2nd par.	1,22,23 9,13,16/1,16/9, 15,17-20
X Y	Yngvesson, Imaging Front End Systems for Millimeter Waves and Sub-millimeter Waves," SPIE Conf. an Submillimeter Spectroscopy (1985) Fig. 12, pgs. 8+9.	1,22,23 9,13,14,1-5,16/1 16/9,17-20
X Y	Johansson et al, "Millimeter Imaging Systems with an Endfire Receptor Array." 15th European Microwave Conf Fig. 1, pg. 1	1,22,23 9,13,15,16/1, 16/9,17-20
Y	US, A, 4,611,912 FALK et al 16 Sep. 1986 Fig. 1, col. 3 line 10 thru col. 4, line 29	3,5,7,8,11,12,21
X	US, A, 4,164,740 CONSTANT 14 Aug. 1979 Figs. 1, 2, 3 col, 5, l. 40-col. 6, l. 7, col. 11, l. 13-20, col. 13, l. 31-47, col. 14, l. 40-44	1
A	Goldsmith, P.F., "Designing Quasioptical Systems", Millitech Corp. Microwave System Designers Handbook, 5th Ed. (1987)	1-24

* Special categories of cited documents: [10]

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

IV. CERTIFICATION

Date of the Actual Completion of the International Search	Date of Mailing of this International Search Report
08 January 1990	13 FEB 1990
International Searching Authority	**Signature of Authorized Officer**
ISA/US	Gilberto Barron Jr. Gilberto Barron Jr.

Form PCT/ISA/210 (second sheet) (Rev.11-87)